Decision Support for Assessing the Feasibility of a Product for Remanufacture

by

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Abstract

Remanufacturing is the process of restoring old, damaged and failed products to a condition *'as good as new'*. Whilst the practice of remanufacture has been conducted for almost a century, the attention it receives within mainstream business is increasing due to potential benefits associated with economic savings and reduced environmental impact. There are several challenges in operating a successful remanufacturing business, one of which is how to assess the feasibility of remanufacturing. Remanufacturing does not lend itself towards every product due to factors related to the product, process, market and business capabilities, therefore careful assessment should be conducted before taking on a remanufacturing endeavour.

This thesis reports the research undertaken to aid decision makers assessing the feasibility of a product for remanufacture. The aim has therefore been to determine the requirements of assessing remanufacturing feasibility, then to develop a tool to support this activity.

Requirements of the decision making process were established through a detailed review of the literature supplemented with additional interviews from remanufacturing businesses, whilst research gaps for support tools were identified through a systematic review of existing tools presented within academia. Through these reviews it was determined that current methods do not provide enough support in determining the impact of uncertainties found within remanufacturing against key assessment criteria, such as economic cost. Focus upon the tool development was therefore directed at estimating remanufacturing cost of a product under uncertain conditions.

The tool was designed, utilising techniques such as Monte Carlo analysis, fuzzy sets and case based reasoning. A prototype of the tool was then implemented within an object oriented structure and deployed as web service. Testing and validation were conducted by demonstrating the functionality of the tool against a set of specification requirements, through two contrasting remanufacturing case studies identified within industry.

In summary this research has developed a tool to support the assessment of remanufacturing viability through cost estimation under uncertain conditions, identifying requirements through a detailed literature review and interviews with industry and providing validation through two detailed case studies. The tool is novel in its ability to calculate both cost and the risk associated with the uncertainties present within the remanufacturing domain.

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1 Introduction

1.1 Background

In an increasingly competitive global marketplace, western manufacturers in particular are struggling to compete purely on cost with emerging market nations, predominantly due to the difference in the price of labour. As a result these manufacturers are focusing upon adding value into their product offerings to enhance quality, thus increasing customer satisfaction to therefore justify the relatively higher costs. One way in which this is being achieved is through the selling of not just products but complementary services or even combined product service solutions. These aim to maintain and enhance performance throughout the product's life, through services such as condition monitoring, maintenance programs and other aftermarket services.

However, to provide these additional services, businesses often need to adjust in order to meet the challenges which this service provision imposes. One such issue is providing a secure and cost effective supply of spare parts in order to satisfy long term maintenance services. This can become a challenge for some traditional manufacturers, as emphasis has usually been placed upon producing a narrow set of new products in high volumes, taking advantage of economies of scale. This business model however does not suit the aftermarket service well, as the range of products catered for within service contracts is often larger but in much lower volumes. Whilst manufacturing new spare parts is an option, in many cases the cost and time of doing so is unfeasible due to the high costs of maintaining specific tooling, small batch production and additional storage. One possible solution to this problem is to incorporate remanufacturing into a business's service offerings.

Remanufacturing is a form of reuse, in which damaged or discarded products are restored to the standards of a newly manufactured equivalent (Thierry et al.:1995, Ijomah:2009). Remanufacturing differs from other forms of reuse, such as repair or reconditioning, as a warranty is given equivalent to a newly manufactured product. It has been described as the ultimate form of recycling as it not only reclaims the material content of a discarded product, but also retains the embodied energy used during the original manufacturing process (King et al.:2006). This can potentially reduce the cost of producing products whilst also minimising the environmental impact by reducing resource consumption and waste.

The service of remanufacturing can be useful for many businesses involved with the product service aftermarket. It can be used as an effective supply of spare parts, reducing the need for long term storage and maintaining specific tooling to manufacture products from new. It can also be used as a direct service, where customers pay to have their products remanufactured. Additionally some manufacturers may use remanufactured components within leased products, such as Xerox (Kerr, Ryan:2001).

Although remanufacturing may seem an attractive proposition to add to a business's portfolio, it may not be suitable in every situation. Factors such as the product design and the condition of returned cores can increase the overall cost of remanufacturing, making it less desirable relative to alternate options. Insufficient demand for the remanufactured products can also lead to business incurring losses through high storage costs. Additionally customer satisfaction can be negatively affected if supply of remanufactured products cannot meet demand, or, if the quality of remanufacturing does not meet the desired standards. It is therefore important to carefully assess the viability of remanufacturing at all levels of a business, from strategic planning, right through to the operational inspection of individual product cores, in order to determine its suitability. This decision is often complicated by the relatively high level of uncertainty present in remanufacturing systems.

1.2 The Research Question

Within this thesis the primary research topic of interest is the assessment of whether to conduct remanufacturing. After initial consultations with businesses involved in remanufacturing, it was decided that an interesting research avenue would be to investigate how these decisions could be better supported. The following research question has therefore been drawn for this PhD research;

How can the assessment of product feasibility for remanufacture be better supported?

1.3 Aims and Objectives of the Research

After consideration of the research question, the following aim has been formulated for this thesis;

To understand the problem of feasibility assessment in remanufacturing and determine what factors must be considered and how related decision making can better be supported.

To address the above research aim the following objectives have been outlined;

1. Identify the requirements and factors used in assessing product feasibility for remanufacture.
2. Identify and evaluate methods and tools which help assess remanufacturing feasibility and identify gaps in the research.
3. Design and implement a novel tool to support the assessment of remanufacturing feasibility.
4. Test and evaluate the proposed support tool.

Objective 1 is designed to explore the requirements of the assessment of remanufacturing feasibility in depth, with the specific aims of understanding the key factors that affect the decision, the different levels at which the decision occurs within a business and the key challenges in making the decision. The outcome of this objective will enable assessment criteria to be developed and used in objective 2.

Objective 2 is used to assess the current work in tools and methods to assist this decision process. Its purpose is to identify gaps in the current research and show how current tools could be improved.

The purpose of objective 3 is to develop a tool designed to meet the requirements of assisting the assessment of remanufacturing feasibility. The specifications for the tool are determined using the findings from objective 1 and 2.

Finally objective 4 outlines the need to test and evaluate the proposed support tool to ensure it meets the specified requirements.

1.4 Research Methodology

Due to the intended software development within this research project, a software development methodology has been used to guide this PhD research. A large number of software development methodologies exist including the Waterfall model (Royce:1970), Spiral Model (Boehm:1988) and Rational Unified Process (RUP) (IBM:2014). The research methodology used within this thesis predominantly follows the waterfall model used for software development, shown in Figure 1-1.

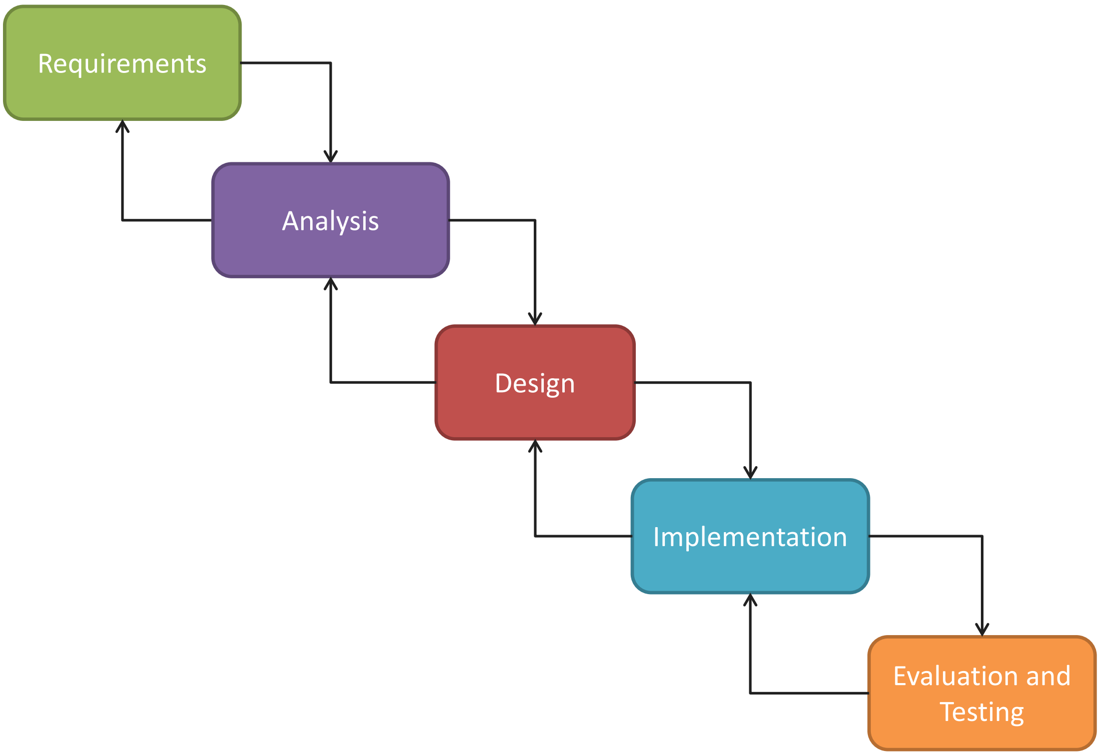


Figure 1-1 The Waterfall Methodology

The outline of the waterfall method was first conceived by Royce (1970) who identified the need to include additional stages when developing large software systems, to expand the simplified analysis and coding approach. Whilst the term waterfall is often used to describe this method, indicating a cascading linear and non-iterative transition from one development stage to the next, this in fact incorrect as Royce never used this to describe the proposed methodology and in fact advocated an iterative approach.

The exact number of stages often differs between sources, however for the purpose of this research five key stages are outlined; Requirements, Analysis, Design, Implementation and Evaluation and Testing.

- Requirements – Within this stage the justification for a software tool is investigated, through the assessment of the problem domain. Within this thesis this includes a literature review of the problem area, consultation with industry and an evaluation of current proposed academic solutions. A formal specification of requirements for the software tool is then documented.
- Analysis – The analysis phase evaluates possible solutions relative to the requirements outlined in the previous stage.
- Design – Within the design phase the algorithms to be used within the software tool are developed and explained.
- Implementation – The implementation phase encapsulates the detailed design into a software structure. Coding of the software tool also takes place within this phase, although is not detailed within the thesis chapters.
- Test and Evaluate – Here the implemented software tool is tested and evaluated relative to the software requirements outlined in the requirements specification.

Whilst there has been criticism of the Waterfall method (Boehm:1988), these are mainly directed toward its use within commercial software development within large teams, where cross collaboration is conducted between team members and divisions. Due to the nature of this PhD project being an individual piece of work by a single person, the pitfalls of the Waterfall model are not felt. Therefore it is sensible to use this approach for the research methodology.

1.5 Thesis Outline

This thesis is formed through 9 chapters and the structure is outlined in Figure 1-2. After the introduction (Chapter 1), the thesis is split into five distinct stages to mirror the research methodology described in Figure 1-1. The requirements stage develops an understanding of the problem area. Here objectives 1 and 2 are addressed within chapters 2 and 3 respectively. Chapter 4 is then used to focus the scope of the research to a particular set of requirements that are to be addressed within the software tool. The analysis, design and implementation of the software tool in chapters 5, 6 and 7 respectively, contribute to the objective 3. Objective 4 is then addressed within the chapters 8 and 9. This comprises of a validation of the developed solution in chapter 8 and overall research conclusions in chapter 9. A brief summary of the contents of each chapter is given below;

Chapter 1 – Introduction, provides a research background, the research question, aims and objectives, outline of the work conducted and the structure of the thesis.

Chapter 2 – This chapter is used to address objective 1. Using both primary (observations, interviews from industry) and secondary (literature) sources, the decision of how to assess remanufacturing feasibility is investigated, focusing upon the key decision factors, the levels at which this is conducted within the company and the challenges faced in making the decision.

Chapter 3 – This chapter conducts a systematic review of the tools designed to assist the assessment of remanufacturing feasibility. Tools are evaluated based upon key findings from the chapter 2, with the purpose of identifying research gaps.

Chapter 4 - Based upon the findings from the first two chapters, the research focus for the tool development is narrowed and a specific specification for the tool to be developed is presented.

Chapter 5- An analysis of possible solutions is conducted using a literature review. Particular methods and techniques used to address similar problems in alternative domains are analysed, which could be applied to this particular challenge.

Chapter 6- The design of the support tool is detailed. Here the techniques used are explained and the algorithms are described in detailed.

Chapter 7 –The implementation of the tool is detailed. This is provided with an explanation of how the design is implemented into software code, including the overall system architecture and the information structure developed.

Chapter 8 - The support tool is demonstrated and validated relative to the requirements specification outlined in Chapter 4, using two case study examples.

Chapter 9 – Conclusions provide a summary of the research conducted, a discussion regarding the research contributions and future work that could be conducted.

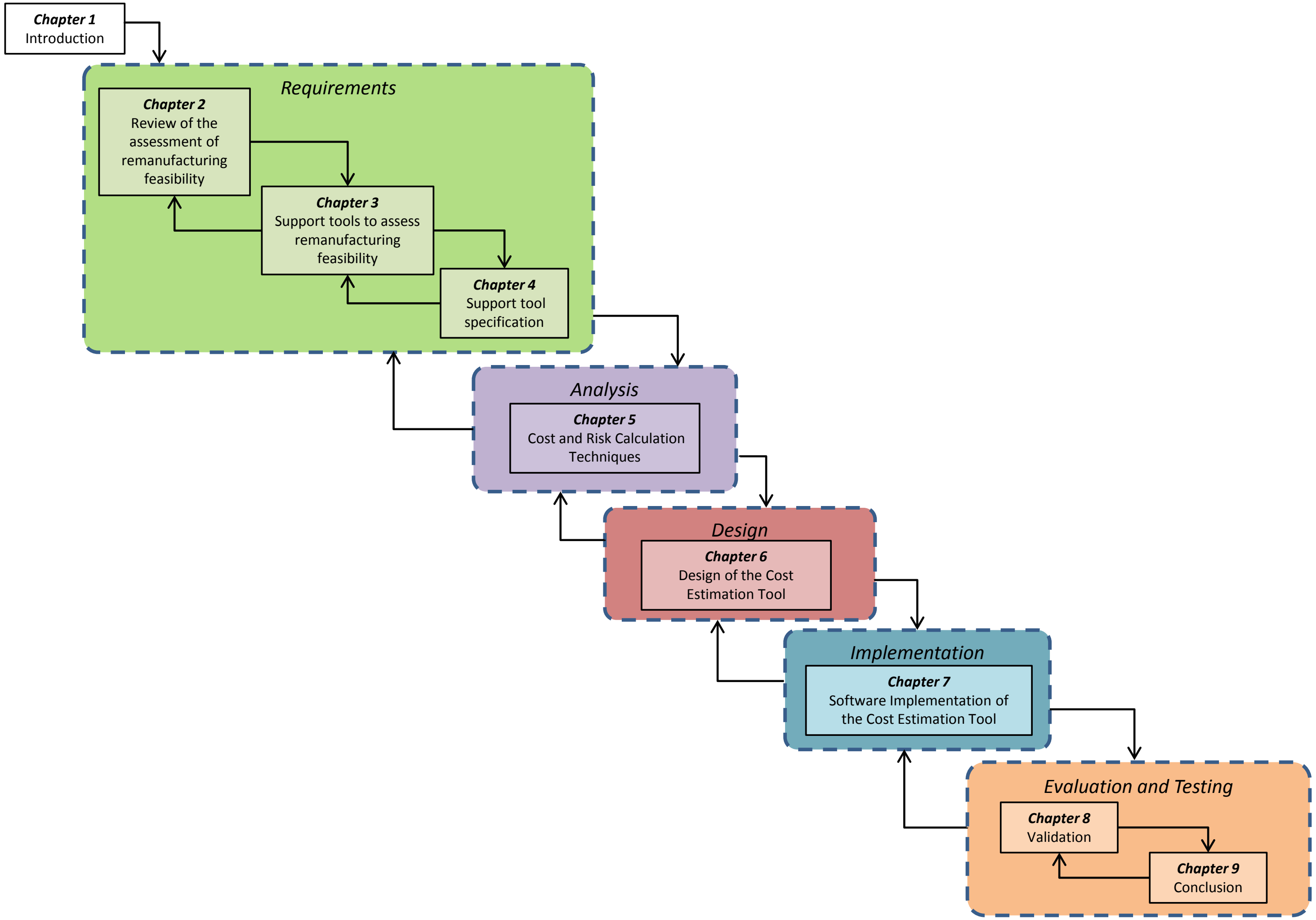


Figure 1-2 Map of thesis structure, identifying the relationship between the chapters and the research methodology

2 Review of the Assessment of Remanufacturing Feasibility

The purpose of this chapter is to develop an understanding of the process for the assessment of remanufacturing feasibility, based on key literature and supplemented through discussions with industry.

2.1 Chapter 2 Introduction

As discussed within the introduction, remanufacturing is not a suitable option for all products and business situations. Deciding whether or not to remanufacture is therefore an important business decision for companies considering or conducting remanufacture. In order to successfully support the assessment of remanufacturing feasibility, an understanding of the decision process is required. The purpose of this chapter is therefore to explore this decision process to develop a greater understanding of its requirements. To achieve this three questions are proposed, which are;

2-a What are the key factors affecting the decision of whether or not to remanufacture?
2-b Who makes this decision and where does it occur within the business?
2-c What are the key challenges to making this decision?

The work conducted in this chapter is as follows; the methodology used to identify the remanufacturing feasibility process is firstly explained. Findings are then presented in the structure of the key factors affecting the decision process, the scenarios in which this decision occurs and finally the key challenges facing this decision process. A conclusion is then presented to summarise the findings.

2.2 Chapter 2 Methodology

To provide an understanding of assessment of product feasibility for remanufacture, a framework of the area is developed. The main source of data for this section is existing literature published in peer reviewed journals. The research is grounded in highly cited journal publications, shown in Table 2-1, and supplemented with additional relevant peer reviewed journal publications and findings from high level case studies, in order to develop and justify the framework.

Table 2-1 Highly cited journal publications within the area of remanufacturing decision making

Article	Decision Category	Total number of Google Scholar citations	Citations per year
Thierry et al. (1995)	Strategic	1043	54.9
Sarkis (2003)	Strategic	619	61.9
Dowlatshahi (2005)	Strategic	122	15.3
Seitz (2007)	Strategic and Tactical	119	19.8
Subramoniam et al. (2009)	Strategic	67	16.8
Östlin et al. (2009)	Strategic	65	16.3

Gehin et al. (2008)	Tactical	114	22.8
Bras and McIntosh (1999)	Tactical	107	7.6
Guide (2000)	Tactical and Operational	533	41
Ijomah et al. (2007)	Tactical and Operational	68	13.6

Five high level case studies have been used within this study. A diverse selection of remanufacturers were chosen (i.e. OEM, independent, high and low value, and high and low volume) to represent the different types of remanufacturers identified. Data was collected in the form of informal interviews and observations from visits to the remanufacturing facilities. Profiles of the case studies can be found in Table 2-2.

Table 2-2 Profiles of the remanufacturing businesses case studies

Name	Business Scenario	Remanufacturer Type	Product	Interviewee	Visit to Remanufacturing Facility?
Case 1	Product/Part Service	Independent Third Party	Wind Turbine Gearbox	Senior Management, Operational Manager	Yes
Case 2	Aftermarket Spare Parts/ Warranty	OEM and licenced third party	Automotive Parts	Factory research management	No
Case 3	Aftermarket Spare Parts/ Warranty	OEM and licenced third party	Industrial machine parts	Factory management	Yes
Case 4	Whole Product/ Aftermarket Spare Parts	Independent Third Party	Automotive Lighting	Owner	Yes
Case 5	Product/Part Service	OEM, licenced third party, independent third party	Gearboxes	Business Manager	Yes

The framework is presented in three sections to answer the specific questions given in section 2.1; Remanufacturing Decision Objectives and Factors, Remanufacturing Decision Stages, and Challenges to Decision Making for Remanufactures.

With remanufacturing often being linked to sustainability (Mayyas et al.:2012, Rathore et al.:2011), the framework of the three pillars of sustainability which are economic, environmental and social, will be used to categorise the unique decision factors businesses should consider when assessing the feasibility of remanufacturing. Decision stages have been categorised based upon traditional managerial decisions which are strategic, tactical and operational phases.

2.3 Remanufacturing Decision Objectives and Factors

2.3.1 Decision Objectives

The decision objectives are the core drivers for remanufacturing. They have been split into the three sections to reflect the triple bottom line of sustainability, namely economic, environmental and social, as shown below in Figure 2-1.

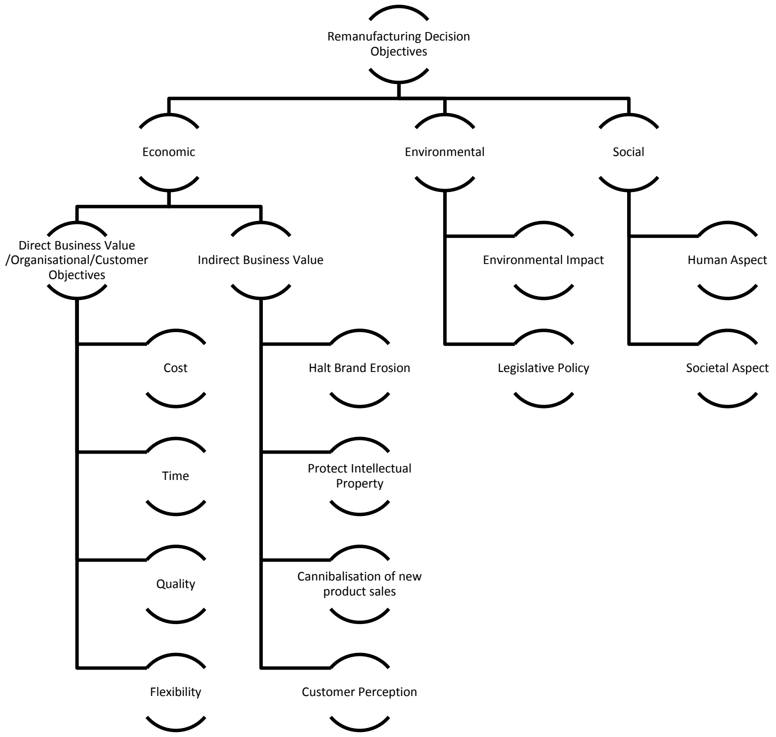


Figure 2-1 An overview of the remanufacturing decision factors, adapted from Dunmade (2004)

2.3.1.1 Economic

The economic decision objectives have been split into two categories; direct and indirect. The direct objectives address the value that can be directly obtained from remanufacturing for both business and customers, whilst the indirect objectives evaluate how remanufacturing can affect other aspects of a business such as the businesses brand image and potential cannibalisation of new product sales.

2.3.1.1.1 Direct

In order to be a successful endeavour, remanufacturing must offer some value relative to other options or strategies. Dowlatshahi (2005) notes that ensuring the needs of the customer are met is of primary importance, before establishing a reverse logistics network to enable remanufacturing. Sarkis (2003) also highlights the importance of assessing the performance criteria of reverse logistics options such as cost, quality and time, relative to other strategies. Remanufacturing has been shown to be a valuable strategy within a number of business scenarios, shown in Table 2-3. Depending upon the business scenario, remanufacturing can potentially offer customer benefits through reduced cost and time and improved quality, compared to alternative strategies.

Table 2-3 Business scenarios in which remanufacturing takes place

Business Scenario	**Product Example**
Whole Product Remanufacture	Single use cameras (Matsumoto, Umeda:2011)
Aftermarket Spare Parts	Automotive spare parts (Subramoniam et al.:2009)
Warranty (OEM or licenced third party)	Electronic game consoles (Walsh:2010)
Product/ Part Service	Wind Turbine Gearboxes (Case 1 and Case 5)
Product Service System (PSS)	Photocopiers (Kerr, Ryan:2001), Aero Engines (Ijomah:2009)

Economic savings within remanufacturing, relative to traditional manufacturing, are primarily attributed to reduced material and processing costs. These arise from the reuse of a product which enables both the material content and the embodied energy of the original manufacturing process to be retained (Thierry et al.:1995). However, it should be noted that remanufacturing also accrues additional costs which manufacturing will not incur. These costs occur in remanufacturing through the need of reverse logistics and additional processes such as disassembly and inspection (discussed further in the next section on Decision Factors). Additionally, where manufacturing takes place in high volumes, processes can become more efficient by taking advantage of economies of scale. Remanufacturing may struggle to compete with manufacturing on cost when it is conducted on this scale, as it tends to occur in smaller volumes and includes labour intensive processes such as disassembly (Kerr, Ryan:2001). When mass production of products and components ends, then the opportunity for remanufacturing occurs as seen in the automotive spare parts industry (Seitz:2007, Inderfurth, Mukherjee:2008).

If cores are available, then remanufacturing may be a faster way of replacing a product or component than with a newly manufactured one, particularly when normal production has ceased, no stock is available or when there is full capacity at the manufacturer’s facility. Case 2 cited reduced lead times of producing remanufactured parts for the automotive aftermarket as one of the key drivers for remanufacture, particularly for rare items which are no longer mass produced and would therefore require custom manufacture. Reduced lead times is also an important factor within the wind energy business, as highlighted by Case 1 and Case 5, as downtime to replace components stops wind turbines generating power and thus revenue. Walsh (2010) describes how the standardised remanufacturing process enabled Sony PlayStation to reduce lead time on their aftermarket warranty service. This is done by moving away from a repair business model, where the customer returns an individual product which is then repaired and sent back to the customer, to remanufacturing where a replacement remanufactured product is sent back to the customer whilst the returned core is remanufactured and then stocked ready to be sent to another customer. This is only acceptable as the customer knows that the remanufactured product conforms to a high quality warranty as good as new.

The quality of the goods produced by remanufacturing is another important objective for remanufacturing. The quality can be perceived in two ways; firstly the physical quality of the finished good in relation to the warranty it is given, and secondly the performance quality relative to the performance attributes. The physical quality of remanufactured products is higher than those of other End of Life (EoL) strategies such as repair, or refurbishment (Thierry et al.:1995). However, the perceived quality of remanufactured goods tends to be less than those that have been newly manufactured. This perceived value gap is even greater within the Business-to-Customer (B2C) market opposed to the Business-to-Business (B2B) (Atasu et al.:2008). This is largely due to B2C products having a considerable fashion emphasis whereas B2B products are purchased predominantly for their functional attributes. The performance quality of a remanufactured good is relative to the current performance of an equivalent newly manufactured product. This means that if the performance criteria changes rapidly, such as through technological or fashion changes, then remanufactured products will be less desirable as they are fixed with the performance criteria from the product design, although upgrades are sometimes possible.

2.3.1.1.2 Indirect

There are also indirect consequences of remanufacturing which business should also consider within their decision. Cannibalisation of new product sales is a concern for many OEMs (Atasu et al.:2008, Guide Jr, Van Wassenhove:2009). Many OEMs fear that a percentage of their new product sales will become lost as a result of remanufacturing. Brand erosion and the protection of intellectual property is a concern for OEMs whose products may be remanufactured by third parties (Subramoniam et al.:2010). When remanufacturing is conducted by third parties, the OEMs have no control over the level of quality that the work is conducted to. However, as the product still bears the OEM’s name and identity, poor quality remanufacturing may still be linked to them, thus potentially eroding their brand image (Seitz:2007).

2.3.1.2 Environmental

Remanufacturing activities are becoming more and more attractive due to the benign environmental impacts associated with them (King et al.:2006). Proactive businesses may see remanufacturing as a method of greening their business activities, whilst environmental legislation may force businesses to consider the environmental effects of their actions.

By conducting remanufacturing, products which may else have been sent to landfill, can be given extended life cycles, such as that found within Case 3. This can potentially reduce the need to manufacture products from new, thus saving precious natural resources. The remanufacture of a starter motor has the potential of saving nine times the quantity of material and use seven times less energy than to manufacture from new (Matsumoto, Umeda:2011), whilst the process of engine remanufacture has been quoted as using 83% less energy than a newly manufactured equivalent (Smith, Keoleian:2004). Remanufacturing is also seen as environmentally preferable to other EoL options such as recycling as not only is the material preserved but also the ‘embodied energy’ from the initial manufacturing processes. However when assessing the environmental impacts of remanufacturing the savings gained over manufacturing from new must be compared to the potential impact in prolonging products where technologies have been superseded with more energy efficient means. In many cases a product’s environmental impact can be much greater during the use phase of their life than during the manufacturing stage which is an important factor to consider when evaluating the environmental impact of remanufacturing (Gutowski et al.:2011). Many remanufactured products also do not have to conform to the latest environmental regulation policy, only that of which they were required to at the time of their original manufacturer, which is the case for Case 3.

Although governmental directives and legislation have often been attributed as an incentive to conduct remanufacturing activities (Barker, King:2006, Guide:2000), the weight of this assumption has been questioned by some researchers within literature. The End of Life Vehicles (ELV) directive designed to reduce waste within the automotive industry has been criticised by Gerrard & Kandlikar (2007) in that it does not encourage higher forms of waste management hierarchy such as remanufacturing, instead promoting recycling and energy recovery. Seitz (2007) also questions the effect of ELV as a driver for engine OEM’s who conduct remanufacturing and, based upon industrial interviews concluded that little evidence could be attributed to the ELV directive being directly attributed to the decision to remanufacture within this sector.

2.3.1.3 Social

Dyllick and Hockerts (2002) split the social aspect of sustainability into two categories; the human aspect and societal aspect. The human aspect concerns factors such as skill, motivation and loyalty of both employees and business partners, whilst the societal aspect concerns the communities in which businesses conduct their activities. Within remanufacturing literature several factors which can affect decision making have been discussed that fit into this category.

From a consumer perspective remanufacturing can offer low cost alternatives to many high quality products. There is also the opportunity of additional job creation as at present remanufacturing tends to be a labour intensive task due to processes such as disassembly being required (Parkinson, Thompson:2003). However, remanufacturing may allow old technology, which has been superseded by products boasting improved safety, to remain in use and available in the market place (e.g. motor vehicles). Companies must also consider the safety aspects of remanufacturing processes such as potential risks within the disassembly process (e.g. spring loaded parts) and the potential interaction with hazardous substances (chemicals, oils etc.) for both employees and local residents (Presley et al.:2007).

Remanufacturers must ensure that the work they conduct meets particular quality and safety standards (Dowlatshahi:2005). Case 5 indicated that the electrical equipment being remanufactured must conform to particular electrical standards before being sold. It is important therefore, that decision makers assess the viability of meeting these standards when making the decision as whether to remanufacture.

A key feature of remanufacturing is the level of customer satisfaction it can offer particularly within the aftermarket, which can also be included within the social aspect of the sustainability (Hubbard:2009). The option of remanufactured parts and components can reduce the cost to the customer whilst prolonging the life of the overall product in which the remanufactured component is used. Economically it may be more desirable for the business to sell new products at a higher cost however by sharing the benefits of lower cost, high quality products that remanufacturing can offer can lead to strong long lasting customer relations desired by a sustainably minded business. Seitz (Seitz:2007) found this to be one of the motives for business to conduct remanufacturing.

2.3.2 Influencing Factors

To assess the objectives for assessing the feasibility of remanufacturing, discussed previously, an understanding the factors that will effect remanufacturing is required. Where in the previous section the discussion was on why decision makers would choose a remanufacturing strategy, this section addresses how specific factors can affect the objectives. These factors have been subdivided into four categories; product, process, market and business, as shown in Figure 2-2. Whilst each factor can be discussed individually, their impacts and relationship with each other are intrinsic, thus it is important to not only assess the effects of each upon the key objectives, but also each other.

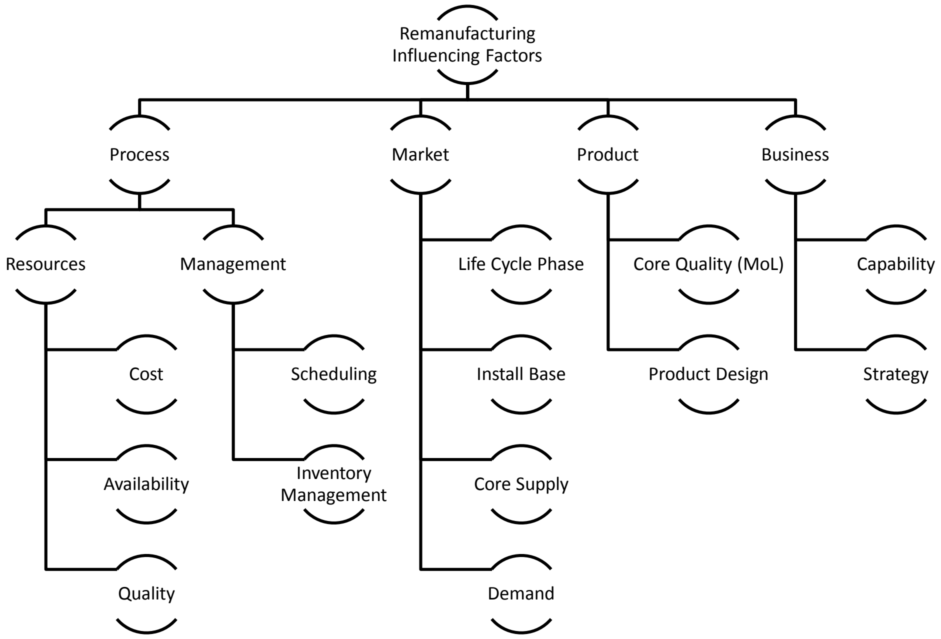


Figure 2-2 Remanufacturing Decision Factors

2.3.2.1 Process

Understanding the remanufacturing process is one of the most important factors to understand as it directly affects many of the direct decision objectives. Although the exact process conducted by each remanufacturer will differ, they all comprise of a common set of generic activities. Understanding these activities is important as the resources which they consume directly affect the cost, time and environmental impact of remanufacture. These generic activities are logistics, disassembly, inspection, cleaning, storage, rework, assembly and testing (Sundin, Bras:2005).

The logistics of moving a core to the remanufacturing facility, is an important activity to consider. Often the cost of transportation can outweigh the value of remanufacturing, particularly if the product is of low value. Lead time of transportation can also become an important factor to assess, particularly if specialist equipment is required which has often limited availability, such as in offshore wind turbines identified by Case 5. Disassembly is the deconstruction of a product to enable access and remove individual components and subassemblies. Disassembly can either be categorised as destructive or non-destructive, with the former requiring components to be irreversibly damaged to gain access to internal components. Inspection is the analysis of a product, assembly or component to establish its physical condition and determine an appropriate course of action, such as reuse, remanufacture or disposal (Sundin, Bras:2005). An inspection can take several forms ranging from quick visual examination, to detailed measurement analysis. Cleaning is the procedure of removing dirt and debris from the product or component, enabling inspection or rework to take place. Storage is required by many remanufacturing processes, to stock cores and spare parts which may be difficult to obtain on the market place. Rework is the process in which individual components are restored to their original specifications. This process will often require multiple activities involving techniques such as surface treatment and machining. Assembly takes the reworked components, as well as those that have been replaced with new, and assembles them to form the remanufactured product. Testing allows a remanufacturer to assess the quality of the remanufactured product to ensure it meets the required standards. This is an important activity for remanufacturers as it gives them confidence that the product will meet the required quality standard.

The resources required by each activity can be broken down into labour, materials and overheads. The resources required are by no means fixed for each activity, and can vary significantly between similar product types for a number of reasons including the physical EoL condition of the returned product, product design, and overall process efficiency (affected by batch size and inventory control) as highlighted in Figure 2-3.

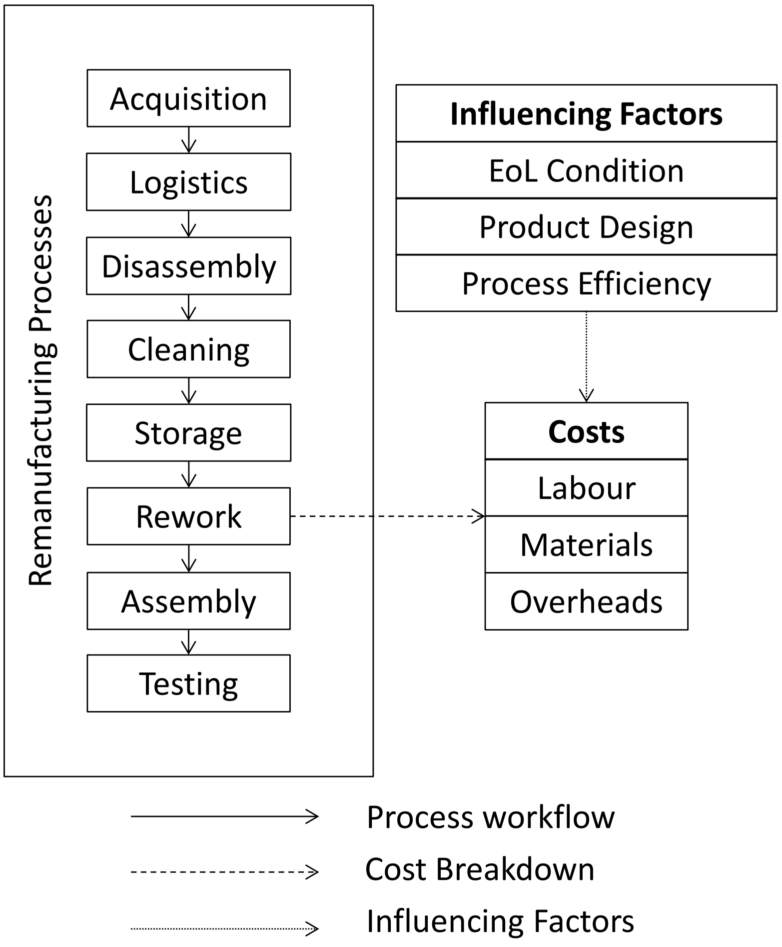


Figure 2-3 Break down of the generic remanufacture process with costs and the factors that affect these shown for the rework stage

The management of remanufacturing facilities can also impact the objective criteria. When remanufacturing facilities are not operating at optimum levels inefficiencies will occur, affecting objectives such as cost and time. This can occur when insuffícent cores are available to remanufacture, or when the variability of product type is too large (Guide:2000). This can lead to issues such as bottle necks within the production system, capacity constraints and overstock or under stock of inventory resources.

A number of tools have been developed to assist remanufacturers with optimising these production planning and inventory control issues and are discussed in greater depth by Ilgin and Gupta (2010).

2.3.2.2 Market

Market factors are split into two areas, the availability of cores to remanufacture and the demand for the remanufactured product.

To conduct remanufacturing a supply of cores is required. Cores can become available for remanufacture when the product has either functionally failed, or it has become obsolete. However, accessing these cores is not straight forward. Many remanufacturers will not have access to information about the product whilst in use so will be unaware once a product has reached the criteria to be remanufactured. Additionally owners may not be aware that remanufacturing is an option for their used product, thus may look to dispose it through other means. Therefore remanufactures must establish reverse logistic channels to access cores and provide incentives, usually financial, for owners to utilise them.

The demand for remanufactured products varies with time and is heavily linked to factors such as obsolescence (Ayres et al.:1997). This is influenced by factors such as advances in technology (Guide:2000) and fashion (Ijomah et al.:2007). Whilst demand for a particular product is higher during the earlier to middle phases its product life cycle, it is often more cost effective to manufacture these products from new, due to the advantages of mass production. However, when manufacturers cease high volume production of a product in its later life cycle phase, remanufacture can become a more attractive option, increasing its demand (Inderfurth, Mukherjee:2008).

In order to exploit the benefits of remanufacturing, both product demand and a supply of used cores are required. Where the demand and availability of cores overlap, the opportunity for remanufacture to be of value exists, as highlighted in Figure 2-4. Sarkis (2003) highlights the importance of the product life cycle phase within strategic decision making. For further information see Östlin (2009), who provides a detailed explanation of this area.

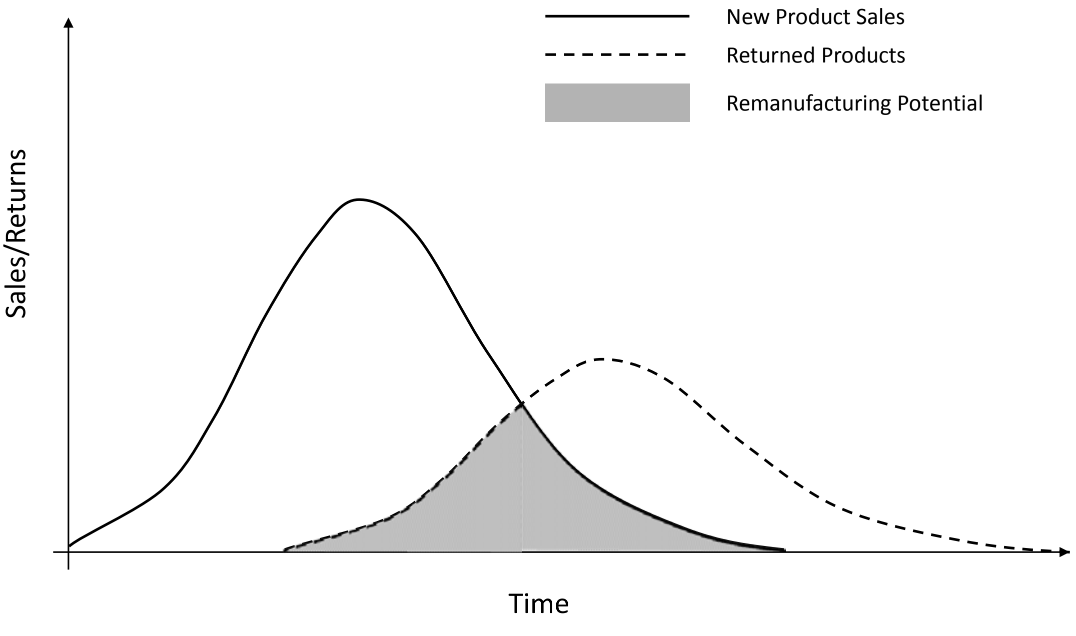


Figure 2-4 Volume of demand (product sales) and return rate over the life cycle of a product, with potential for remanufacturing highlighted through the overlap of the two curves.

2.3.2.3 Product

The product being considered for remanufacture will have significant influence upon all of the decision objectives. Two aspects of the product are discussed, the design of the product and the physical condition of the product.

The product design can have significant impact on the cost of the remanufacturing processes. Sundin and Bras (2005) link product properties such as ease of identification, verification, access, handling, separation, securing, alignment, stacking and wear resistance with the generic remanufacturing processes shown in Figure 2-3. For example, the ease of separation can be affected by the joining method of internal components. Difficultly in disassembly can increase the process time, number of separating tools and probability of damage to the product, thus increasing the total cost (Sundin, Lindahl:2008). Design for remanufacture aims to improve the potential for a product to be remanufactured and is discussed in greater detail by Hatcher et al. (2011).

The condition of the returned core will have a significant influence upon the process required to remanufacture. The difference between the condition of the returned product core and the required final quality level of remanufacturing has a significant influence in the overall cost (Jun et al.:2007). Higher wear and damage may require more expensive process techniques in order to return a component to the required quality level (Östlin et al.:2009). For example worn gears must be either reworked or replaced in order to remanufacture the entire gearbox. Light wear can require surface finishing, whilst heavy wear entails grinding and if damage is too severe then replacement is required (Michaud et al.:2011).

2.3.2.4 Business

Factors relating to the business assessing remanufacturing feasibility, such as their capabilities and resources, product relationship and strategy, will impact upon the decision objective criteria.

Understanding the strengths and weakness of a business relative to the requirements of remanufacturing can play a significant role in the adoption of its practice. Making use of current resources can be an important way of reducing the overall cost of remanufacturing (Dowlatshahi:2005). Utilising the capabilities of other aspects of the business, such as logistics networks, manufacturing of key components, skills and equipment can enable a significant advantage over competitors and alternative options. Having to invest in additional facilities, equipment, infrastructure and skill base can result in a higher costs, which may lead to remanufacturing becoming an unattractive option.

The relationship which the business has with a product will also play a role in the information flow. Remanufactures who are also the OEM will have information about the products' Beginning of Life (BoL), including detailed product designs, and potentially Middle of Life (MoL) information relating to sensor readings from condition monitoring systems, scheduled maintenance reports and even customer information which may be useful in locating cores. Access to this information can reduce the uncertainty surrounding a product to be remanufactured and may lead to reduced processing time and costs, explained in greater depth in section 2.5.

The strategy which a business adopts may also encourage or hinder its potential for remanufacturing. Strategies in which a business retains ownership of a product, such as a leasing business or a product service system (PSS), enable the business to maintain a relationship with the product and thus ensure it can be returned at the EoL for remanufacture.

2.4 Remanufacturing Decision Stages

The assessment of remanufacturing feasibility is not confined to one aspect of a business. This decision can be found at different levels from high level strategic management, through to operators assessing individual products on the shop floor. Whilst this decision in principle is the same, the aims and factors influencing the decision can differ.

Within this section three decision stages are analysed, strategic, tactical and operational. The strategic decision is further split into policy making and business, whilst tactical decisions are sub divided into design and EoL. Each decision is assessed for its aim and to identify the key objectives and influencing factors.

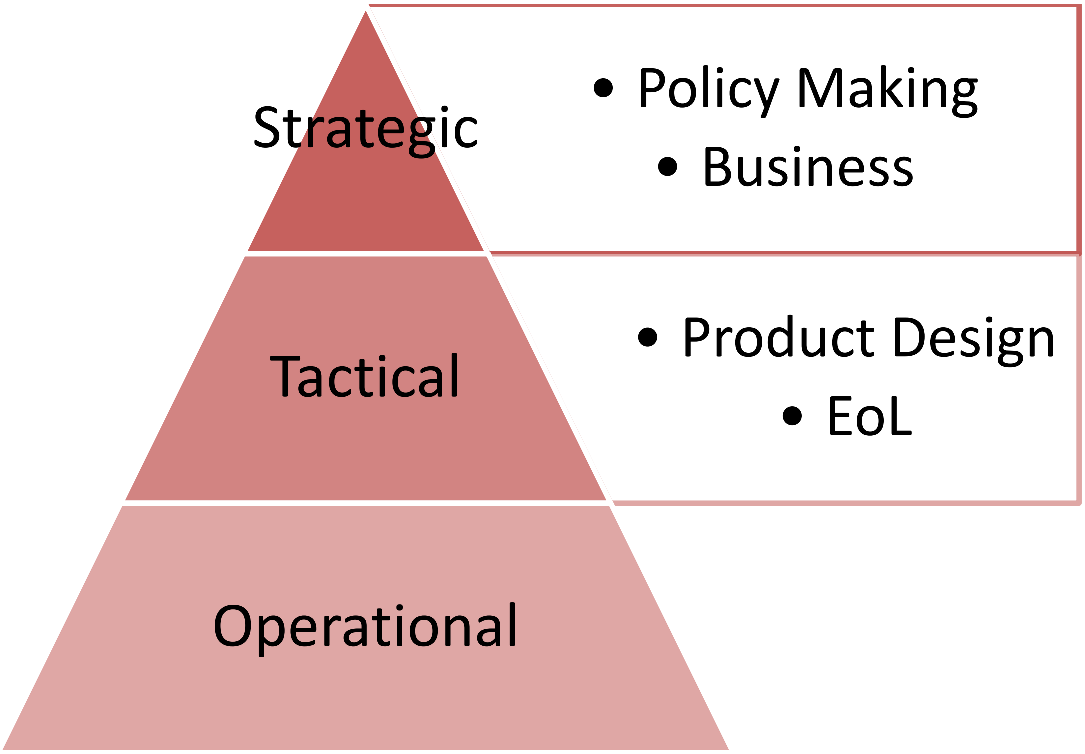


Figure 2-5 Overview of the decision stages

Table 2-4 Summary of the decision stages for assessing remanufacturing feasibility

Decision Stage	Key Purpose	Information contained within product description	Potential Users
Strategic	Provide early feasibility analysis of adopting remanufacturing within a business strategy	General Product Type	High level/senior management/ middle management
Tactical	Evaluate a particular product design for remanufacture. Can either be used in the product design phase, or in the operational planning phase.	Specific Model, product structure and BoM maybe included	Middle management/ operational management/ design engineers
Operational	Evaluate a specific product for remanufacture. Can occur remotely using MoL information or during inspections at the remanufacturing facility.	Detailed product structure including information related to condition of the product. Additional process information may also be provided such as inventory levels and factory capacity.	Middle management/ operational management/

2.4.1 Strategic

2.4.1.1 Policy Makers (Government)

Strategic decision making regarding the adoption of remanufacturing, can be made at a governmental level. Although these decisions do not directly force business to adopt, or dismiss remanufacturing, their effects upon policies can significantly influence businesses decisions, as highlighted within the strategic decision factors identified within Table 2-6. Examples of governmental policies that have been introduced to reduce waste through encouraging product EoL responsibility (although not directly remanufacturing) include Waste Electronic and Electrical Equipment (WEEE) and ELV.

No direct study has been conducted assessing key factors driving policy making for remanufacturing, however it can be assumed that sustainable thinking is at the heart of governmental decisions, thus economic, environmental and social factors will all be of importance. The factors affecting these decisions should be addressed at a holistic level rather than for specific businesses. Table 2-5 highlights the key decision objectives involved with making this decision, as well as the factors that should be considered.

Table 2-5 Summary of strategic policy making decision

Strategic Policy Making			Assessment of whether to support and encourage remanufacturing activities made by governments and policy makers.				
Decision Objectives				**Decision Factors**			
Economic		**Environmental**	**Social**	**Process**	**Market**	**Product**	**Business**
Direct	**Indirect**						
X	X	XX	XX	X	X	X	X

2.4.1.2 Business

Strategic decisions made at a high level within a business (by senior management) are aimed at shaping its long term future. Within the context of this research, the aim of the decision is to assess whether remanufacturing is a suitable strategy for the particular business. This decision is usually taken prior to the establishment of remanufacturing activities and additionally at periodic stages to review whether it is having the desired effect on the business. Scenarios in which remanufacturing have been successfully incorporated into a business are shown within Table 2-3.

OEMs may additionally make strategic decisions regarding the EoL of products at the conceptual product design phase, particularly when they have invested interests such as found within the Product Service System (PSS) business scenario. If remanufacturing is deemed a preferred option for a product's EoL, then steps can be taken to incorporate specific features constructive to remanufacturing into the design (Gehin et al.:2008).

A number of studies have been conducted which evaluate the factors affecting strategic decision making within remanufacturing (Subramoniam et al.:2009, Subramoniam et al.:2010, Subramoniam et al.:2013). The key findings from these studies identify that the most important factors affecting the adoption of remanufacturing lie within the economic factors identified within section 2.3.1.1 were most relevant, as shown the list of factors in Table 2-6.

Table 2-6 Key remanufacturing decision factors and their descriptions identified by Subramoniam et al. (2013)

Factors	Factor description/question	Relative weighting scores for the different factors
Financial impact of reman	Does your understanding of financial impact of reman influence your decision to reman?	0.300
Core management	Does the process to recover new cores (reverse logistics) influence your decision to reman?	0.175
Intellectual property	Does the need to protect the Intellectual Property of the product positively influence your decision to reman?	0.115
Green perception	Does a "green" perception of reman products, with respect to energy and environment; for example, influence your decision to reman?	0.083
OE product specifications	Do OE customer product specifications and requirements with respect to reman, influence your decision to reman?	0.081
Government regulations	Do current government regulations influence your decision to reman?	0.078
Organizational alignment	Does the need for a well-integrated organizational alignment between your OE and aftermarket divisions influence your decision to reman?	0.069
Design for reman	Does a product's design, with respect to ease of (re)manufacture, influence your decision to reman?	0.061
Brand erosion	Do the outside reman competition and the resulting brand erosion positively influence your decision to reman?	0.035
Product recovery value	Does increased product recovery value positively influence your decision to reman?	(included in financial impact)
Disposal costs	Does the increasing speed of technology change, and the resulting disposal costs, positively influence your decision to reman?	(included in financial impact)
Intrinsic recovery value	Do the cores (or used parts) having high intrinsic value to be recovered from the customer positively influence your decision to reman?	(included in financial impact)
Product life cycle costs	Does a product designed with consideration of product life cycle costs influence your decision to reman?	(included in financial impact)
Upfront financial Investment	Does the need for upfront financial investment negatively influence your decision to reman?	(included in financial impact)

Whilst environmental and social factors do influence strategic decisions, they are not the primary driving force and are usually motivated by governmental regulations and the positive marketing effects of a green perception. A summary of the key decision objectives and factors can be found in Table 2-7.

Table 2-7 Summary of the strategic business decision

Strategic Business	Assessment a business looking to adopt a remanufacturing strategy						
Decision Objectives				**Decision Factors**			
Economic		**Environmental**	**Social**	**Process**	**Market**	**Product**	**Business**
Direct	**Indirect**						
XX	XX	X	X	X	X	X	XX

2.4.2 Tactical

Tactical decisions tend to be focused toward the medium term, with the aim of providing a method for implementing the chosen strategy. Within the context of assessing remanufacturing as an EoL option the tactical issue involves the planning of the remanufacturing business, more specifically determining which products are to be considered for remanufacture, also described as the disposition decision (Ferguson et al.:2011). Unlike the strategic phase where information about a product is contained to a high level, such as the general type e.g. an engine, the tactical phase assesses particular product types and models, thus containing a greater depth of information. This decision has been identified at two stages within a business. The first is during the product design, whilst the second occurs close to the products' EoL within the planning and management at the remanufacturing facility.

2.4.2.1 Design Stage

The product design stage is the first opportunity at which decisions can be made about specific EoL strategies of products and components within a products' life cycle. Here designers can analyse a specific design and determine the most suitable EoL strategy for each of the components. Modifications can be made to the design to enhance the remanufacturability of the product, such as grouping components with similar EoL strategies.

The key factor that influences this decision is the product design and in particular how it affects the remanufacturing process and the market. Sundin and Bras (2005) discusses the relationship between product design features and its influence upon the generic remanufacturing activities, as shown in Table 2-8.

Table 2-8 RemPro matrix showing the relationship between product design characteristics and generic remanufacturing activities (Sundin, Bras:2005)

Remanufacturing Activities **Product Characteristics**	Inspection	Cleaning	Disassembly	Storage	Repair	Reassembly	Testing
Ease of Identification	X		X	X			X
Ease of Verification	X						
Ease of Access	X	X	X		X		X
Ease of Handling			X	X	X	X	
Ease of Separation			X		X		
Ease of Securing						X	
Ease of Alignment						X	
Ease of Stacking				X			
Wear Resistance		X	X		X	X	

Additionally the product life cycle must also be considered, with the anticipation of component failure rates, and market demand for a product based upon customer requirements and product obsolescence.

Whilst design stage decision making has received attention from academic researchers, its inclusion within industry remains questionable. Within the businesses interviewed for this study, of which three were OEMs and thus had the ability to influence design decisions, none said the consideration to remanufacture influenced the product design. Instead the decision whether to remanufacture was held until the product neared its EoL at the remanufacturing facility, thus falling into the second of the two tactical decision stages outlined above.

Table 2-9 Summary of the tactical design stage

Tactical Design		Assessment of a product at the design phase for potential to remanufacture.					
Decision Objectives				**Decision Factors**			
Economic		**Environmental**	**Social**	**Process**	**Market**	**Product**	**Business**
Direct	**Indirect**						
XX	O	X	X	X	X	XX	O

2.4.2.2 Remanufacturing Facility

Decisions occurring at a remanufacturing facility differ to those at the design stage due to the relatively shorter time frame between the decision taking place and remanufacturing occurring. The impact of these decisions will have direct impact upon the operational remanufacturing activities. The tactical decision of whether to remanufacture at the remanufacturing facility can take several forms, depending upon the type of business scenario in operation. Examples of this type of decision include;

- Determining methods of supplying aftermarket spares for a particular product or component

- Evaluating remanufacturing contracts
- Evaluating core suppliers
- Determining general EoL strategy for a product and components

Performing a full detailed analysis of whether to remanufacture each time a product is received requires a large amount of resource, adding to the overall cost of remanufacture. For low cost and high volume remanufacturing this level of analysis for each product instance can be expensive and time consuming, therefore it can be useful to develop general rules and heuristics at a tactical level to guide operational decisions. In the case studies analysed, this type of decision occurred within all of the businesses, although the degree to which this occurs varies. Case 3 conducts a detailed analysis before a product model is accepted for remanufacture within the plant. For remanufacturers of products of higher value and lower quantities the tactical assessment of products is conducted on a per product basis. Case 1 estimates cost and time required to remanufacture a product for a customer to determine if they would like to proceed.

Within the case study examples, identified in Table 2-2, there are several examples of this decision taking place. Case 2 provides two examples of how this decision is undertaken. The first is based upon a service business model. Here maintenance contracts are agreed with the customer for a number of years. At periodic intervals engines are remanufactured to ensure the long term maintenance of these products. As contracts are agreed over for a number of years it is important to assess the cost well in advance to ensure the business is not placed under unnecessary risk. The decision here is whether to offer a contract to remanufacture and under what circumstances (cost, time, quality). The second policy is based upon an aftermarket spare parts business. Individual products are sourced from the open market using a buy back scheme. Customers receive a discount when purchasing remanufactured products if they trade in their old product. Providing the old product meets certain requirements regarding the product type and condition a rebate is given. The decision here is to evaluate which type of products should be included within the buyback scheme and what price should be offered for cores. This not only sources particular cores, but also attracts business to purchase remanufactured products.

The objectives of this decision will vary between remanufacturers depending upon the strategic objectives set in place. Economic factors and in particular the direct factors related to cost, quality and time, will be the most common factors assessed at this stage. Indirect economic, environmental and social factors may also be considered, however the frequency of these factors was less within the case studies analysed relative to the direct economic factors.

All of the factors highlighted within section 2.3.2 should be considered when addressing this decision stage. The effects of the key influencing factors that need to be addressed by decision makers are highlighted in Table 2-10. These relate to the product cores, the managerial policies and the additional resources required to remanufacture.

Table 2-10 Summary of the tactical EoL decision

Tactical EoL	Assessment of a specific product type, but not a specific product instance. The decision is taken in the medium to short term by decision makers involved with the remanufacturing facility.						
Decision Objectives				**Decision Factors**			
Economic		**Environmental**	**Social**	**Process**	**Market**	**Product**	**Business**
Direct	**Indirect**						
XX	X	X	X	XX	XX	XX	X

2.4.3 Operational

Operational decisions are those which are encountered on a day to day basis. Within the context of assessing remanufacturability, this type of decision focuses upon assessing individual products and components. The purpose of these decisions is to determine the most suitable action for each particular product being assessed, thus ensuring resources are not unduly wasted through unnecessary processing whilst not omitting potentially useful cores. The key difference between this and the strategic and tactical decisions is that products are assessed on an individual level and at the time remanufacturing is due to take place, rather than for generic product types and at a time well in advance of remanufacture taking place. Therefore the uncertainty of factors such as demand, supply and condition are less than at the strategic and tactical phase. However, uncertainty will not completely be eliminated, and will remain in factors such as product condition until full disassembly is conducted.

An example of this type of decision is during the product inspection. The purpose of an inspection is to gain a crisper understanding of the physical condition of a particular product, thus reducing the uncertainty of this key decision factor. Product inspections are a key activity within the remanufacturing process and can occur at multiple stages, as shown in Figure 2-6. Inspections can be a costly process, requiring resources to physically disassemble and conduct measurements. Therefore many businesses choose to use multiple inspection stages, employing simple, cheaper inspections at an earlier stage to filter out unwanted cores early in the process, to reduce the cost of expensive detailed inspections at the later stages. One of the challenges with this decision is ensuring accuracy with early inspections and not rejecting cores that have the potential to be remanufactured. Some remanufacturers are beginning to investigate utilising data recorded from a products MoL to form part of the product inspection (Case 1 and 2), which enables assessment remotely from the remanufacturing facility, This 'remote' inspection can potentially save upon logistical costs, although requires sufficient infrastructure to be available, such as embedded sensors and condition monitoring networks, in order to collect and analyse the information. This type of inspection has been discussed within literature by several authors (Jun et al.:2007, Klausner et al.:1998).

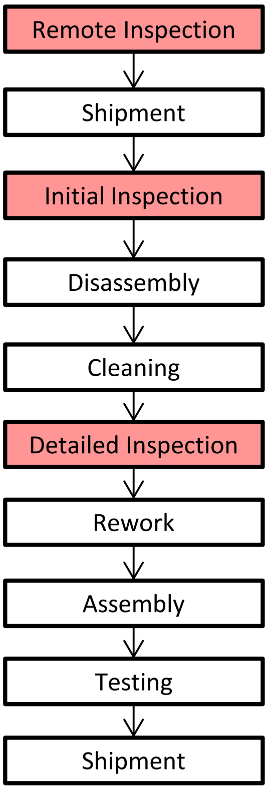


Figure 2-6 An example remanufacturing process with inspection phases highlighted

Physical condition is not the only factor influencing this decision stage. The need to balance supply and demand is critical to the remanufacturing business. Ensuring an inventory of cores are available for customers is important in reducing the lead time, however excess inventory can lead to additional storage costs. Table 3-1 summarises the key objectives and decision factors for the operational decision.

Table 2-11 Key factors affecting operational decision making

Operational	Assess an individual product for remanufacture, either at the factory during product inspections, or just prior to arrival						
Decision Objectives				**Decision Factors**			
Economic		**Environmental**	**Social**	**Process**	**Market**	**Product**	**Business**
Direct	**Indirect**						
XX	O	X	X	XX	X	XX	O

2.5 Challenges of decision making for remanufacturing

The key factor which complicates remanufacturing decision making relative to traditional forward manufacturing, is the high level of uncertainty associated with the return of product cores. This uncertainty stems from the lack of information flow between early life cycle phases (in particular the use phase) and the remanufacturer. There are three main uncertainties present in remanufacturing systems; the condition (Galbreth, Blackburn:2010, Guide:2000), the design and physical structure (Ijomah:2009), and the timings and quantities of product returns(de Brito, van der Laan:2009, Ferrer, Ketzenberg:2004, Inderfurth:2005).

The condition of products being evaluated for remanufacturing will vary considerably due to the uncertain nature of the use phase of their life (Guide:2000), where the operational environment, users, tasks and time will all vary from product to product. The design and physical structure may vary throughout the life of a product with upgrades and modification potentially occurring. If the original product designs are not available to the remanufacturer then it further adds to the uncertainty at the remanufacturing stage. The timing and quantity of product returns are also likely to be unknown as it is usually the user that determines when it is to be relinquished, not the remanufacturer.

The effects of these uncertainties are strongly felt within the remanufacturing environment. Strategic decisions, which are already required to deal with uncertain information due to their long term nature, are further complicated with these specific uncertainties. Östlin (2009) discusses how these uncertain factors can hinder the ability to anticipate and exploit product life cycle trends, such as timing and quantities of product returns. Uncertainties regarding the condition and product structure can lead to uncertain process routing, as the full set of activities required to complete remanufacture will not be known (Guide:2000). This can make it difficult to predict performance metrics such as cost, time and environmental impact of remanufacturing. Unknown timings and quantities can cause problems for production planning and inventory control, which can reduce the overall efficiency of the remanufacturing plant through process bottle necks, unfavourable lot sizing and carrying of unnecessary inventory. All of these uncertainties can therefore make it difficult to predict metrics, such as remanufacturing cost, which are used within remanufacturing decision making. Understanding these uncertainties and their impacts are therefore important when assessing the risk associated with a decision.

It should be noted however that the level of uncertainty within a remanufacturing system can vary greatly depending upon the solutions which may have been implemented to reduce it. The relationship that the remanufacturer has with the OEM may dictate the information available from the manufacturing stage to aid with remanufacturing, such as the product design, manufacturing dates and quality test results. The amount of information feedback throughout a products' useful life will also significantly affect the uncertainty at the remanufacturing stage. Regular contact with the product, through service and scheduled maintenance, can enable data to be recorded throughout the product lifecycle. Additionally the use of technologies such as embedded sensors can enable monitoring of a products' condition during the use phase of its life cycle, thus allowing real time diagnostics to take place (Ilgin, Gupta:2011, Jun et al.:2007). This can enable remanufacturers to know the condition of the product prior to its arrival for remanufacture and also when it may be returned, reducing uncertainty within these areas. Contracts with suppliers and incentives to return cores can also be used to help reduce these uncertainties (Ijohmah, 2009).

Table 2-12 Identifying the sources, effects and solutions to uncertainty within remanufacturing

Uncertainty Source	Effect on decision making			Solutions
	Strategic	**Tactical**	**Operational**	
Returned core condition	Added complexity in identifying the effect of long term decision factors	Assessing the impact of uncertainties upon performance metrics such as cost, time, quality and environmental impact	Measuring and quantifying core quality accurately	Multiple inspection stages, obtaining MoL product information,
Returned product type and design information			Determining the evaluation criteria	Links to OEM to obtain product information, effectively store product information obtained from experience
Timings and quantities of returns			Complicating inventory and production planning issues	Contracts with core suppliers, offer cash back for cores

Finally the reliability and availability of information on which a decision is based can add further uncertainty. This is perhaps more prominent during strategic and tactical phases, when information can be based upon long range forecasts which are often difficult to predict, but may also occur in short term decisions such as the operational phase, when the information required is not accessible or is unknown due to inexperience. Whilst this problem is not isolated to remanufacturing, the uncertain nature of remanufacturing and uniqueness of each remanufacturing job can make estimating decision factors difficult. This issue was encountered within Case 1 and 2.

2.6 Chapter 2 Summary

A review of the assessment of remanufacturing feasibility has been conducted predominantly though the use of peer reviewed literature publications and the addition of five high level industrial case studies. The purpose of this review has been to form a framework to understand the requirements and challenges faced by this decision, as outlined within objective 1 of the thesis. To establish this framework three sub objectives were defined (2a, 2b and 2c).

Objective 2a addressed the objectives and influencing factors of the decision to remanufacture. The objectives which are used to evaluate this decision have been highlighted and categorised using the three pillars of sustainability and are summarised in Figure 2-1. Key factors that affect this decision have been grouped in relation to the process, the market, the product and the business.

Objective 2b addressed the areas in which these decision tools are targeted. Decision making can be split into three key areas; strategic, tactical and operational decisions. Each area has been discussed with key decision factors assigned to each of the phases. Whilst aspects of factors from the three pillars of sustainability can be found within each decision phase, their importance can vary. Strategic decisions tend to require a more holistic assessment and thus require greater input from the three decision criteria outlined, whilst the tactical and operational phases tend to be more focused upon the economic factors although specific environmental and social factors can be addressed if they are deemed important from strategic management such as conforming to legislative policies.

Objective 2c asks to identify the challenges faced by remanufacturing decision making. The key challenge identified was the relatively high level of uncertainty associated with the remanufacturing process. This can lead to difficulties whilst assessing decision factors as the information in which these factors are being assessed will carry this uncertainty.

The findings from this chapter will now be used within Chapter 3 to guide the assessment of tools aimed at supporting the decision of whether to remanufacture.

3 Support Tools to Assess Remanufacturing Feasibility

This chapter is used to identify research within literature designed to provide support for assisting the decision of remanufacturing feasibility. A systematic review of the literature is conducted to identify and evaluate related work to understand the current state of the art and identify gaps in the research.

3.1 Chapter 3 Introduction

The challenge of assisting businesses in the decision of assessing remanufacturing viability, or problems along a similar theme, is not new and has been investigated by several academics. Similar themes like EoL product decision making, in which a product is assessed against a number of EoL strategies such as reuse, recycling and disposal, are common place within literature. However, there currently is not a comprehensive review of these decision tools relative to the requirements of assessing the viability of remanufacturing. The purpose of this chapter is to satisfy the requirements of objective 2 which states to '*determine what methods and tools have already been developed to help assess remanufacturing feasibility and identify gaps in the research'*.

In order to satisfy this objective a review of the relevant literature aimed at assessing remanufacturing feasibility has been conducted within this chapter. The structure of the remaining chapter is as follows; after this introduction a methodology is presented explaining how the review was conducted, including how the material was collected and evaluated. Next, results are presented based upon the defined categorisation. A discussion regarding the results and their implications are presented, before the overall findings and conclusions are drawn.

3.2 Chapter 3 Methodology

A content analysis has been conducted for this chapter. In contrast to traditional or narrative literature reviews, a content analysis uses a clear research procedure and explicitly states methods for selecting and evaluating publications (Boehm, Thomas:2013). This approach enables greater transparency to the entire review process, thus giving the study greater scientific validity as the process becomes repeatable. This type of review is frequently used within the medical and pharmaceutical domain and is becoming more popular within the business studies area. Three key stages are outlined within the methodology of the study (Boehm, Thomas:2013), these are:

1. Scope of the study
2. Search Strategy
3. Evaluation of material method

The first step is to define the scope of the study by delimiting literature, defining clear boundaries of what is and is not to be included. The delimitations of this study excluded publications as follows;

- older than 10 years (before 2003)
- tools designed to assist with production planning of remanufacturing, reverse logistics and disassembly sequencing, as these focused upon optimising a process rather than addressing the key subject of this paper that is to determine whether to conduct remanufacture.
- the analysis was limited to English written peer reviewed journal papers or published conference papers.

The first delimitation of the study is to exclude publications before 2003. This allows for the previous 10 years to be analysed, to focus on the most up to date tools and methods. The second delimitation is based upon the decision that the tool and method supports. The intention of this research is to focus upon the decision of whether to remanufacture. Tools which do not meet this key requirement are therefore excluded. This exclusion includes tools aimed at optimising production planning and inventory management decisions, reverse logistics planning and disassembly sequencing. Although these areas overlap and can influence the decision making process, ultimately they seek to optimise a particular aspect of remanufacturing, rather than decide whether or not to remanufacture. Finally the study is limited to English written peer reviewed journal papers or published conference papers.

The search strategy used for collecting material for this review is now discussed. The approach is described in Figure 3-1. Firstly a structured keyword search of three well established bibliographic databases was conducted to obtain relevant material. The databases chosen for the search were Compendex, Scopus and Web of knowledge. These databases were chosen due to their wide coverage of the engineering and manufacturing domain, along with the inclusion of key academic journals within the area, such as the Journal of Cleaner Production and International Journal of Production Research. All keywords searches contained the term ‘Remanufactur*’ using the wildcard ‘*’ to ensure results also included the terms such as remanufacture, remanufacturing and remanufacturability. This was coupled with additional keywords associated with decision making such as evaluation and assessment. Full search terms and results are shown in Table 3-1. A combined total of 1352 papers were found from this initial search.

Table 3-1 Keyword search results for each database (note each keyword was coupled with the term 'remanufactur*' using the & operator)

Keyword Search	Web of Knowledge	Compendex	Scopus
Feasibility	47	77	55
Assessment	61	98	80
Evaluation	75	153	91
Decision making	161	142	151
Decision support	26	34	33
Decision Tool	21	22	25

Duplicates were then removed to leave a total of 558 unique publications. A two stage manual search was then conducted of the individual publications to remove those outside of the delimited criteria. The first involved viewing the publication title to remove those that were clearly outside of the delimited scope. The abstracts of the publications remaining were then viewed to further remove those outside the scope of this study. After the manual search process 41 publications were identified as being relevant to this study.

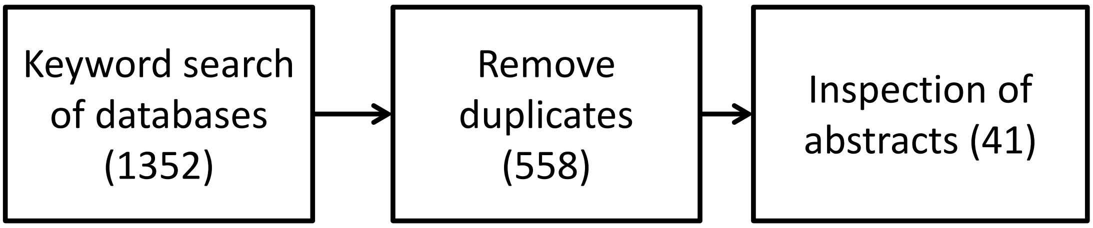


Figure 3-1 The material collection methodology

Finally the approach used to evaluate the material is described. Each article found is categorised based upon specific decision stage of the tool, as shown in Figure 3-2. These categories were generated using the decision levels identified in the previous section; Strategic (policy making and business), tactical (product design and remanufacturing facility) and operational. Using the background summary of the decision making process from Chapter 1, each tool is then evaluated upon how it meets the demands of the decision making process. Table 3-2 shows the specific analytic categories which the tools are evaluated against.

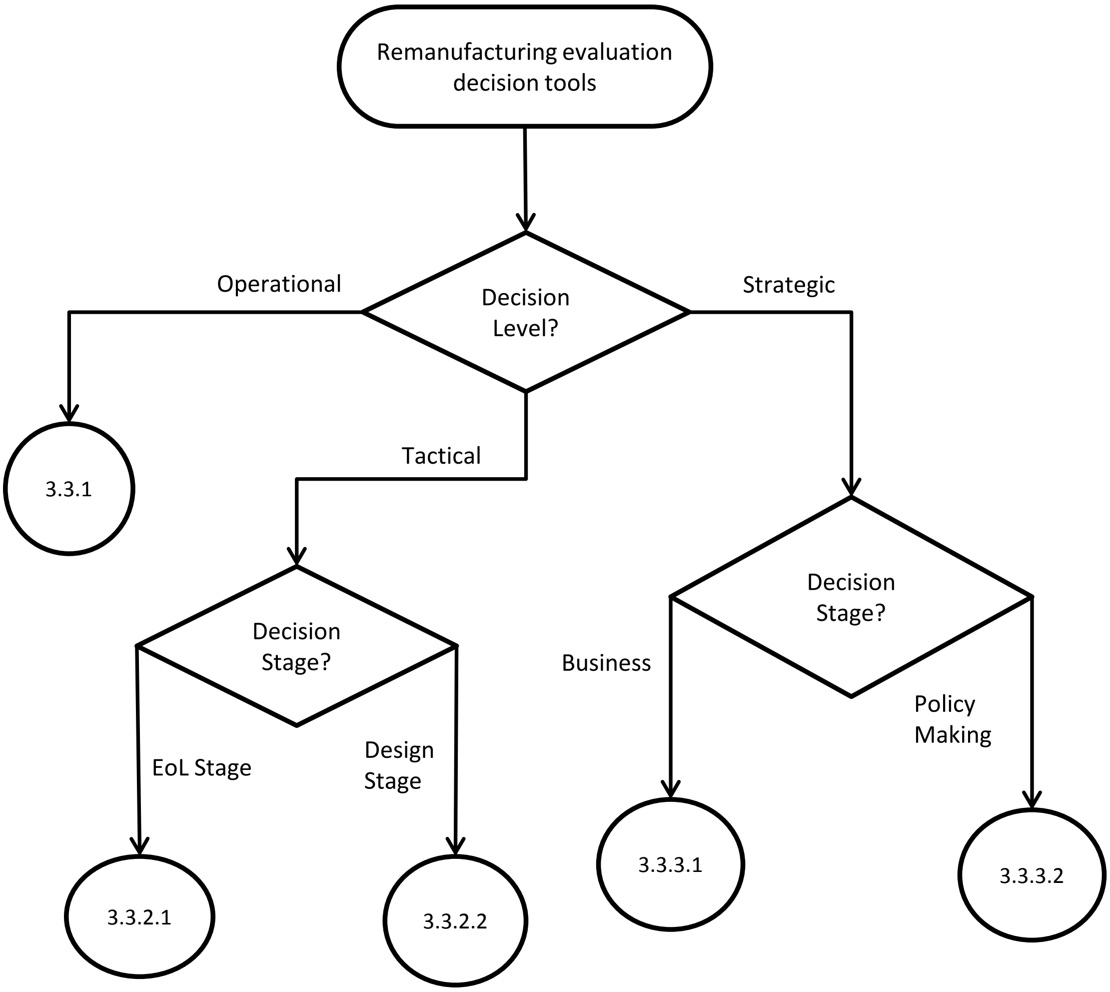


Figure 3-2 Process for categorising tools based upon functionality

The key analytic assessment categories chosen to evaluate the tools were as follows; the decision objectives, the decision factors used to assess feasibility and how well uncertainty is factored into the decision making process. After analysing the tools and methods further categories were included; the type of data input, the purpose of the tool. A full description of each analytic category can be found in Table 3-2.

Table 3-2 Categories used to analyse tools

Analytic Category	Description
Tool Description	Brief description of the tool
Decision Objectives	Which decision objectives discussed in section 2.3.1 have been addressed
Decision Factors	Which decision factors discussed in section 2.3.2 have been addressed
Data input type	Quantitative (Quan) or qualitative (Qual)
Considers Uncertainty?	Factors for uncertainty within data input, including the factors which have been addressed O = Decision factors not considered X = Partial consideration of decision factors XX = Decision factors well covered

3.3 Support Tools for Remanufacturing

3.3.1 Operational Tools

Operational tools are summarised in Table 3-3. These are used to evaluate a specific product instance for remanufacture, such as which occurs within a remanufacturing facility during the inspection phase. The important aspect which is considered here is the condition of the product that is being evaluated for remanufacture. Zhou et al (2012a) focuses upon evaluating the quality of the product for remanufacture, through the assessment of several measurements and inspections. A reusability score is then calculated using a fuzzy Analytic Hierarchical Process (AHP). In some of the tools, the condition is assumed to be known prior to arrival at the remanufacturing facility, through technologies such as sensor embedded products (Jun et al.:2007, Jun et al.:2012). Using this information regarding the product EoL condition, Jun et al (2007) develop a cost model to assess the best EoL strategy for components within a Turbocharger. Jun et al (2012) expands upon this approach to consider multiple products with interchangeable components, and individual conditions for each component within the product.

Table 3-3 Operational Tools

Paper reference	Tool Description	Decision Objectives	Decision Factors	Data Input Type	Considers Uncertainty?
Zhou et al (2012a)	Quality evaluation model to assess reusability and component management system.	Quality	Product Condition	Quan	X (Product Design)
Jun et al (2012)	Product recovery optimisation algorithm to minimise cost under quality constraint	Cost, Quality	Product Design, Product Condition, Process Activities	Quan	O
Jun et al (2007)	Product recovery optimisation algorithm to minimise cost under quality constraint	Cost, Quality	Product Design, Product Condition, Process Activities	Quan	O

3.3.2 Tactical Tools

The aim of these tools is to evaluate a particular product design to determine appropriate end of life strategies for individual components. This evaluation is of a specific product design in which sub-assemblies and components are represented using a Bill of Materials (BoM). The difference between these tools and the operational ones above is that factors, such as product condition, market supply and demand, are not assessed on an individual product basis, but forecast based upon expert knowledge, or historical data sets. The use of these tools includes evaluating best practice for remanufacturing facilities at the EoL and evaluating product designs.

3.3.2.1 EoL Stage

The EoL stage tools are shown in Table 3-4. The majority of tools found here evaluate the remanufacturability of products and components through the comparison of decision objectives of alternate EoL strategies, such as recycling and disposal. Objectives related to economic criteria have been widely used in determining the EoL strategy, in particular the cost.

Evaluating these criteria is often conducted either by a direct analysis of decision factors upon the criteria of cost, time and environment, or when this is difficult to quantify, through alternative metrics. To evaluate the cost objective a value analysis is often conducted in which the price of a remanufactured product is compared to the cost of remanufacturing. The cost can either be directly estimated (as done by Anityasari and Kaebernick (2008)) or via a breakdown and analysis of the generic activities such as disassembly, cleaning and rework, as conducted by Ghazalli and Murata (2011). Xanthopoulos and Iakovou (2009) go into greater depth by accounting for additional costs of production planning issues such as emergency procurement, backorders and emergency set up costs.

Alternatively metrics can be used as an indicator of remanufacturing costs, rather than a direct economic analysis. Factors considered when creating these metrics include ease of conducting remanufacturing activities (Du et al.:2012), product condition via predicted failure rates (Anityasari, Kaebernick:2008, Kumar et al.:2007, Pandey, Thurston:2010a) and variability within a product design (Pandey, Thurston:2010b). These indirectly enable the evaluation of economic factors described in section 2.2.

Environmental factors have been considered by many of the tools during decision making. Quantitative metrics have been used within several of the tools to calculate environmental impacts. The Eco-indicator 99 metric developed by PRé Consultants (2000), which considers damage to human health, ecosystems and resources, has been used by Shrivastava et al (2005) and Zhang et al (2004), whilst other methods express environmental costs as pure economic values (Ghazalli, Murata:2011). Social factors have been partially assessed by Shrivastava et al (2005) and Zhang et al (2004) within the eco-indicator 99 metric, which includes human health scores (PRé Consultants:2000).

Table 3-4 Tactical EoL stage tools

Paper reference	Tool Description	Decision Objectives	Decision Factors	Data Input Type	Considers Uncertainty?
Behdad et al (2012)	A stochastic programming model based upon uncertain return quantity to determine level of disassembly and component EoL strategy	Cost	Product Supply, Product Demand, Market Value, Process Activity, Product Design	Quan	XX (Market Supply)
Du et al (2012)	An integrated method for evaluating remanufacturability of used machine tools	Quality, Cost, Environment	Product Design, Process Activities	Mixed	X (Process Activity)
Ghazalli and Murata (2011)	Component EoL strategy selection algorithm	Cost, Environment	Product Design, Process Activities	Quan	O
Cao et al (2010)	Deployment model for part reuse in customised design of remanufactured products	Cost	Product Design, Product Condition, Product Management	Qual	O
Lee et al (2010)	Component EoL strategy decision algorithm and disassembly sequence optimiser	Cost, Environment	Product Design, Process Activities	Quan	O
Pandey and Thurston (2010a)	A method for making component level EoL decisions based upon component criticality and remanufacturing system variability.	Cost, Quality, Environment	Product Design, Process Activities, Product Condition, Process Management	Qual	X (Product Condition)
Xanthopoulos and Iakovou (2009)	An algorithm to select product EoL strategy and optimise recovery operations	Time, Cost, Environment	Process Activities, Process Inventory, Product Design,	Mixed	XX (Product Condition, Market Supply, Market Demand)
Anityasari and Kaebernick (2008)	A method for evaluating reliability of products for reuse and remanufacture	Cost, Quality	Product Condition, Product Design, Market	Quan	XX (Product Condition)
Kumar et al (2007)	An EoL decision method based upon a model to characterise the value flow during a product lifecycle	Cost, quality	Product condition, Market	Quan	X (Product Condition)
Gonzalez and Adenso-Diaz (2005)	Component EoL strategy decision algorithm and disassembly sequence optimiser	Cost, Environment	Product Design	Quan	O
Shrivastava et al (2005)	A web based system for evaluating product EoL	Environment, Social, Cost	Product Design, Process Activities	Quan	O
Zhang et al (2004)	A web based system for evaluating product EoL	Environment, Social, Cost	Product Design, Process Activities	Quan	O

Six of the tools enable uncertainty within decision factors to be conveyed. Quantitative techniques such as stochastic simulation and Monte Carlo analysis have been used to enable the expression of parameters such as return quantity (Behdad et al.:2012, Xanthopoulos, Iakovou:2009), product life span (Anityasari, Kaebernick:2008) and product demand (Xanthopoulos, Iakovou:2009). Qualitative techniques have been employed when it has been difficult to express a factor in a quantitative manner. Du et al (2012) use a scoring system (1-10) to allow expert users to qualitatively express the pollution reduction through remanufacturing. The failure rate of a product has also been expressed as a probability (0-1) based upon expert knowledge (Pandey, Thurston:2010a, Kumar et al.:2007).

3.3.2.2 Product Design

The second set of tools aimed at a tactical level have been developed to assist with the product design stage. Designers can use these tools to evaluate the suitability of a product design for remanufacture and make adjustments if required.

Economic factors again play the largest role within the decision making process. However, as the decision is being assessed at the beginning of the product life cycle rather than at the end, greater uncertainty is present, as values need to be forecast.

The use of metrics to evaluate decision factors has been widely adopted within these tools, which avoids the need for a direct cost analysis. Xing et al (2007), and Xing and Luong (2009) develop metrics in order to evaluate a products' upgradeability through remanufacture based upon technological, functional, physical and structural factors. A mixture of quantitative and qualitative data inputs are used to construct the metrics. Quantitative values are used to evaluate current and future product performance metrics, whist fuzzy logic is used to express values which are difficult to quantitatively evaluate, such as component link strength.

Krill and Thurston (2005) use a direct quantitative approach in calculating economic cost and environmental impact to assess the effects associated with sacrificial cylinder liners to enable remanufacturing of engine blocks. An activity based model is employed to determine original production and remanufacturing costs, whilst environmental impacts are calculated using a commercial Life Cycle Assessment (LCA) package. LCA has been used solely to determine the environmental impacts for remanufacturing products such as engines (Adler et al.:2007), and telecommunications equipment (Goldey et al.:2010). Emphasis here is placed upon comparing remanufacturing to manufacturing using quantitative environmental factors such as energy consumption, CO2 emissions and material waste.

Table 3-5 Tactical product design stage tools

Paper reference	Tool Description	Decision Objectives	Decision Factors	Data Input Type	Considers Uncertainty?
Iberahim et al (2011)	A method for evaluating component remanufacturability	Time, Cost	Product Design, Process Activities	Quan	O
Li and Li (2011)	Technical and economic analysis of remanufacturing through a profit objective function	Cost, Quality	Process Activities, Market	Quan	O
Schau et al (2011)	Life cycle cost model for evaluating product design alternatives and locations for conducting remanufacture	Cost	Product Design, Product Condition, Process Activities, Product Life Cycle,	Quan	X (Product Condition)
Goldey et al (2010)	Life cycle assessment using the commercially available GaBi 4.0 software.	Environment	Product Life Cycle, Product Design, Process	Quan	O
Wang and Tseng (2010)	Methodology to assist product design and component EoL selection through the use of life cycle commonality metrics (LCCM) and economic analysis	Cost	Process Activities, Product Market, Product Design	Quan	O
Xing and Luong (2009)	Mathematical model to assess product for service life extension through remanufacture	Cost, Quality	Product Design, Product Market, Product Condition	Mixed	X (Product Design, Product condition, Market Demand, Market Supply)
Adler et al (2007)	Life cycle assessment of original manufacturing and remanufacturing in engine components using SimaPro 7.0	Environment	Process activities, Product Design	Quan	O
Xing et al (2007)	Mathematical model to assess product upgradeability for remanufacture	Cost, Quality	Product Design, Product Condition, Product Market	Mixed	X (Product Design, Product condition, Market Demand, Market Supply)
Krill and Thurston (2005)	Spreadsheet based tool to estimate cost and environmental impact of using sacrificial cylinder liners for remanufacturer	Cost, Environment	Process Activities, Product Design	Quan	O
Daimon et al (2003)	Decision support method for life cycle strategy by estimating value and physical lifetimes	Quality	Market, Product Design, Product Condition	Quan	X (Product Condition, Market)

3.3.3 Strategic Tools

Strategic decisions are assessed at a high level and can be assessed for a specific business and also at a governmental level during policy making, as discussed in section 2.4.1. Tools to assist both of these decisions have been found and are assessed below.

3.3.3.1 Business

Strategic tools designed to assist business decision making have been split into three categories based upon their function. Three common categories were found; product suitability, business scenario suitability and internal suitability.

Product suitability evaluates the suitability of a product for remanufacture. This is similar to the tactical tools however it is assessed at a higher level which requires less certainty in the product detail, such as the BoM. Business scenario suitability assesses remanufacturing as an option for use within a particular business strategy. Internal suitability assesses the ability of a particular business to conduct remanufacturing. Emphasis is placed upon the internal requirements of the business to perform remanufacturing activities.

3.3.3.1.1 Product Suitability

Product suitability tools are summarised within Table 3-6. These tools evaluate a product for remanufacture or alternate EoL option at a strategic level, thus requires less crisp and tangible information than at either operational or tactical stages. Decisions tend to be made at the product level rather than individual component or subassembly due to the conceptual level nature of the decision.

Economic, including technological factors, are again key to the decision making process and feature in many of the tools. Information such as ‘number of parts’, ‘technology cycle (years)’ and ‘wear out life (years)’ are required by the tools (Gehin et al.:2008, Thomas Chen, Jun-Nan Wu:2003, Ghazalli, Murata:2011). Environmental factors are also used to influence the decision, although these tend to be qualitative in nature. Questions such as *‘If disposed, will the component be harmful to the environment’* are proposed, with linguistic values such as ‘high’ and ‘low’ used to respond to the question (Pochampally, Gupta:2012). Social factors play only a small part in the decision making process, with only minor references to these aspects found.

Due to the conceptual nature of these tools, uncertainty has been largely incorporated into the decision inputs. Bayesian updating and fuzzy logic have been used to enable qualitative linguistic inputs into a quantitative model (Pochampally, Gupta:2012, Pochampally et al.:2004). Case based reasoning has been used by Ghazalli and Murata (2011) to enable comparisons to be drawn with past cases where appropriate EoL strategies have been calculated.

Table 3-6 General EoL classification tools for strategic product suitability

Paper reference	Tool Description	Decision Objectives	Decision Factors	Data Input Type	Considers Uncertainty?
Pochampally and Gupta (2012)	Product EoL decision making methodology	Cost, Environment	Product Market, Process, Product Design	Mixed	X
Ghazalli and Murata (2011)	Product EoL strategy selection algorithm using case based reasoning	Cost, Environment, Social	Product Market, Product Design,	Qual	X
Gehin et al (2008)	A custom built decision tool called Repro², designed to evaluate product suitability to remanufacture based upon product profiles	Categorisation Matching	Product Design, Product Market,	Qual	X
Dunmade (2004)	Product Lifecycle Extension Techniques Selection (PLEATS) model.	Cost, Environment, Social	Process Activities, Market demand, Market Supply, Business Capability, Product Design	Quan	O
Pochampally et al (2004)	Product EoL strategy selection algorithm using fuzzy logic and Bayesian updating.	Cost, Quality, Environmental, Social	Product market,	Qual	X
Chen and Wu (2003)	Extension of the End of Life Design Advisor (ELDA) tool using a neural network model	Categorisation Matching	Product Design, Product Market	Qual	O

3.3.3.1.2 Business scenario suitability

A number of tools have been developed to assist decision makers assessing the impact of employing remanufacturing as part of a business strategy. Business scenarios in which remanufacturing is addressed include spare parts for aftermarket sales (Inderfurth, Mukherjee:2008), and PSS (Spengler, Stolting:2008, Intlekofer et al.:2010).

Spengler and Stolting (2008) evaluate the effect of strategic business decisions such as incorporating design for remanufacturing, the business organisational structure, the returns incentive system and the process capacity upon life cycle product costs. Inderfurth and Mukherjee (2008) assess the potential strategies to fulfil demand for aftermarket spare parts, namely through a long single batch run, frequent but small production batches or remanufacturing.

Boustani et al (2010) evaluate both the economic and environmental consequences of remanufacturing appliances over a product life time. Here product technology improvements are considered overtime, thus energy use within the use phase becomes increasingly important. Intlekofer et al (2010) evaluate the energy implications of a product leasing strategy combined with remanufacturing.

Table 3-7 Business scenario suitability decision tools

Paper reference	**Tool Description**	**Decision Objectives**	**Decision Factors**	**Data Input Type**	**Considers Uncertainty?**
Intlekofer et al (2010)	Mathematical model to compare life cycle energy consumption of different business scenarios	Environment	Market, Process	Quan	O
Boustani et al (2010)	Life cycle costing (LCC) and assessment (LCA) methods used to evaluate the energy savings and economic impact of appliance remanufacture	Cost, Environment	Process Activities, Product Design	Quan	O
Inderfurth and Mukherjee (2008)	Decision support for spare parts acquisition	Cost, Time	Market, Process Management, Process	Quan	XX (Product Market)
Spengler and Stolting (2008)	Life cycle costing model to evaluate the effect of certain business decisions on a product life cycle cost	Cost, Time	Product Design, Product Condition, Market, Process Management, Business Capability, Business Strategy	Quan	XX(Product Market)

3.3.3.1.3 Internal suitability

The last set of business strategic tools evaluates the ability of a business to conduct remanufacturing. These tools are designed to allow businesses to internally assess themselves to determine their suitability for undertaking remanufacturing. Subramoniam et al (2013) provides a decision making framework in which key decision factors are highlighted for assessment. Wang and Li (2011) use neural networks to evaluate the risk within a remanufacturing business, based upon key remanufacturing activities such as acquisition, disassembly and reprocessing.

Table 3-8 Internal suitability decision tools

Paper reference	**Tool Description**	**Decision Objectives**	**Decision Factors**	**Data Input Type**	**Considers Uncertainty?**
Subramoniam et al (2013)	Remanufacturing decision making framework for assessing business suitability for employing remanufacturing operations	Cost, Cost indirect environment, social	Business Indirect, Product Design, Business Capability,	Qual	X
Wang and Li (2011)	Risk assessment for a remanufacturing system based upon neural network	Economic	Process activities, Business Capability	Qual	XX

3.3.3.2 Strategic Policy Making

Tools that support strategic policy making do not focus upon a specific business. Instead they assess the decision objectives from a societal view, thus taking a more holistic approach. The main decision objective addressed within these tools is the environment. Quariguasi-Frota-Neto and Bloemhof (2012) evaluate the eco-efficiency of remanufacturing of mobile phones and personal computers. Here eco-efficiency is defined as the ratio of welfare created to environmental impact. McKenna et al (2013) develop a model to evaluate the energy savings made through direct reuse and remanufacturing with the German automotive spare parts sector.

Life cycle assessments of particular product types have been conducted by have been Yang and Chen (2005), Smith and Keoleian (2004). Both investigate the environmental benefits of remanufacturing engines compared with that of virgin manufacturing.

Table 3-9 Strategic Policy Making

Paper reference	Tool Description	Decision Objectives	Decision Factors	Data Input Type	Considers Uncertainty?
McKenna et al (2013)	A method for evaluating the energy savings through direct secondary reuse and remanufacture within the German automotive sector	Environment	Product Design, Product Market, Process	Quan	O
Quariguasi-Frota-Neto and Bloemhof (2012)	Mathematical model to evaluate eco efficiency remanufacturing versus virgin manufacturing	Environment, social, quality, cost	Product Market, Process,	Quan	O
Yang and Chen (2005)	Life Cycle Assessment of engine remanufacturing	Environment	Process Activities	Quan	O
Smith and Keoleian (2004)	Life Cycle Assessment of engine remanufacturing	Environment	Process Activities, Product Design	Quan	O

3.4 Discussion

3.4.1 Decision Objectives

Economic decision objectives are the most widely used to assess the remanufacturability within the decision tools with 35/41 incorporating these issues. Of these, cost is the most frequently assessed with 30/35 tools assessing this either solely or in conjunction with other objectives. The method for expressing this cost varies considerably, from an explicit quantitative value such as fixed cost for the whole process or a detailed cost model (Krill, Thurston:2005), to implicit qualitative answers to questions such as ‘How difficult is product X to disassemble’. Quality has been assessed through both the condition of the returned product (Zhou et al.:2012b) and also the value of the remanufactured product. This usually relates to the value of the product through its technological and fashion attributes rather than the quality of the remanufactured product i.e. its predicted failure. The time to remanufacture has rarely been assessed within the tools. When it has been considered it is usually as a metric to calculate cost through time based cost functions such as labour rate for disassembly. None of the tools found calculated total time to remanufacture the product to assess the overall feasibility. This would be useful in particular for operational and tactical tools, where lead time is a crucial factor in the aftermarket service, where downtime is a critical factor.

Environmental factors have been widely considered, with 25 tools including these issues within the decision process. The measurement of the environmental impact has been the most proficient means of considering this factor, with the eco-indicator 99 often being used. Additional measurement techniques focus upon specific environmental impacts, such as the Cumulative Energy Demand (CED) employed by Quariguasi-Frota-Neto and Bloemhof (2012) which focuses upon the energy used within a process. Qualitative methods have also been used to indicate environmental factors when quantitative LCA techniques cannot be employed. These may include simple questions such as 'what is the environmental impact of disposal' in which expert user knowledge is required to answer the question. The boundaries on which environmental impacts are calculated vary between the tools. Many purely assess the impact at the EoL, whilst others may include full life cycle effects which may include use phase differences from upgraded or new technologies.

Finally social impacts of remanufacturing took lowest priority within the tools, with only 5 considering these impacts within the decision process. The eco-indicator 99 metric, used by some of the tools, partially covers social factors as it contains a smaller metric called the human health index, which considers damages to human health from environmental causes (PRé Consultants:2000). Social factors are probably most valuable to assess early within the decision process such as the strategic evaluation stage, so future scope is available to include these factors within the business strategy tools.

Additionally some of the tools (Thomas Chen, Jun-Nan Wu:2003, Gehin et al.:2008) do not use a specific objective to determine remanufacturability, rather they base their decision upon the similarity of other features to other product EoL.

Key Findings:

- Economic the most used objective, particularly cost
- Environmental well covered
- Social, time and quality less well covered

3.4.2 Decision Factors

All four of the decision factor categories have been addressed in some form by the tools identified. Factors related to the remanufacturing process have been considered by 30 of the tools. A common process factor assessed is the generic activities that make up remanufacturing. Cost estimation and environmental impact have been evaluated on an activity level by several of the tools. Wang and Li

(2011) also use the generic activities to evaluate the business capability for remanufacture. Although some examples of process management issues were found within tools, they occurred at a much lower rate that the generic activities. It is understood that one reason for the absence of this factor is due to the exclusion of optimisation tools which focus solely upon these issues within this review. However, including these issues within the assessment of remanufacturing feasibility, particularly within the operational stage, would enhance the tools ability to estimate time and cost, in which these issues would affect.

The market influences feature heavily within the tools identified. Tactical and strategic tools in particular evaluate use supply and demand forecasts to assist decision making. Understanding the value of remanufactured products is also important when estimating cost. Methods of determining market value include expert judgement, time based models (Daimon et al.:2003) and rules associated to the product features such as the design cycle (Thomas Chen, Jun-Nan Wu:2003).

The impact of product design factors is the most assessed of all the factors outlined within the decision tools. Features commonly assessed involve the subcomponents and assemblies, their number and type, their arrangement and grouping, their connections, and the performance. The impact of design factors are usually made in conjunction with other factors, for example how the design affects the remanufacturing process. Disassembly cost is often evaluated through the assessment of product connections. Market value is usually linked to product performance.

Product condition is considered by 12 of the tools within the remanufacturing assessment. Within the tactical and strategic tools this factor is estimated based upon the time in use. Only at the operational stage is the condition assessed individually for products and components. None of the tools enable decision makers to relate raw MoL and inspection data, to the direct effects upon the remanufacturing process.

The business factors have been addressed least of all the factors identified in only 4 of the tools. However, as identified in section 2.4 the business factors are really only applicable in the strategic decision phases, of which they featured 4/15 times.

Whilst many of the tools consider at least two of the decision factors within their assessment, a full integration of all of these factors is limited. For example, whilst operational tools were found to consider product design, condition and process activities, they did not include process management or market factors.

The level of detail to which these factors are assessed varies considerably. For example the process activities are assessed by some tools through rough estimates made by experts (Du et al.:2012), whilst others provide detailed cost models relating the activities to other features such as product design and condition (Zhou et al.:2012b).

Key Findings:

- Overall coverage of decision factors is good
- The integration of decision factors is an area which could be improved upon.
- Many factors are addressed only at a high level

3.4.3 Decision Stage

Emphasis within decision tool development has predominately been focused upon tactical and strategic levels. Of the 41 tools assessed within this paper, only 3 have been designed for use at the operational level.

Tactical decision tools were found to have received a relatively large amount of attention from academia. The main focus within these tools is the evaluation of a product design at a component level for remanufacture. This is particularly useful for remanufacturing businesses with a good understanding of the products which will be received for remanufacture, such as OEMs.

Although several tools have been found to help assess product remanufacturability at a high level, more work could be done to allow strategic decision makers to assess how remanufacturing affects particular business scenarios or strategy. Supply of aftermarket spare parts is a major business application for remanufacturing, however few tools were found to specifically assess remanufacturing as an option for satisfying this business scenario.

Key Findings:

- Fewest tools found supporting operational and strategic policy making decision stages
- Tactical tools were the largest category found

3.4.4 Uncertainty

Many of the decision tools found within this study lacked the capability of expressing the uncertainty regarding an input variable. Often a crisp value is required as an input, such as remanufacturing cost, where in reality this figure will carry a degree of uncertainty due to the factors described in section 2.5. The quantification of this uncertainty could allow decision makers to evaluate the associated risk with a decision.

Another issue that was identified was the relatively large information requirement for many of the tools, in particular those that used quantitative techniques. If all the information required is known then this does not cause a problem, however if uncertainty within this information exists, then this may propagate through to the results exposing the decision to unforeseen risk. Many of the tools rely upon expert knowledge to obtain input values, however this can cause problems as they can be prone to bias, maybe difficult to obtain for large quantities of information and will not automatically update when market conditions vary.

Due to the permutations of input data, such as multiple product designs, core conditions, market values and process variations, it may be infeasible to collect all of the necessary data required by some of the tools.

Those that have expressed uncertainty within the tools do so in either a quantitative or qualitative manner. The quantitative approach often involves the use of stochastic programing, used by Behdad et al (2012) and Anityasari et al (2005) to model the uncertainty related to the quantity of returns and process times respectively, via probability distributions and random variables. Fuzzy numbers is another common approach for describing uncertain data inputs via qualitative linguistic expression such as “high” or “low”.

The inability of expressing and evaluating uncertainty within this type of decision can hinder the decision making process. Remanufacturing operates in a relatively high level of uncertainty, thus a degree of risk is attributed with each decision made. Understanding this risk is a key part of decision making. For businesses that operate in lower levels of uncertainty, such as an OEM remanufacturing a high volume of products, this is perhaps less of a concern, however for remanufacturers operating at high levels of uncertainty, such as independent remanufacturers, where less information regarding the products to be remanufactured is available, understanding uncertainty can be of greater importance. The inclusion of uncertainty to evaluate risk within a remanufacturing decision is another potential research area for expansion.

Key Findings:

- Few tools assess uncertainty, particularly within the operational and tactical phases
- Reliance upon large crisp data sets maybe unfeasible in real applications e.g. cost and time for every activity for every product under every condition.
- Risk is rarely expressed i.e. what is the effect of the uncertainty

3.4.5 Limitations

Although a robust and transparent method has been used to develop this literature review the author accepts that a number of limitations exist within the study.

Defining the scope and drawing clear boundaries around the subject area proved to be a large challenge within the study due to the overlap with other similar research areas such as disassembly sequencing, remanufacturing production planning and other product EoL strategies such as recycling. Defining a clear boundary helps to keep the focus of the study concise and relevant. However, there will inadvertently be publications which lie outside this boundary that may have been of value. Within this study the author decided to exclude publications focused upon the optimisation of production planning, inventory management, reverse logistics, disassembly sequencing and mathematical models designed to evaluate the effects of competition within remanufacturing.

As a framework for assessing the decision tools did not exist, the author decided to develop one based upon existing literature and experiences and meetings with industry. This framework, shown in Chapter 2, is presented in the style of a narrative review. Due to time and resource constraints it has not been possible for the author to analyse this material in the same systematic manner in which the review of the decision tools have been conducted. This acts as a limitation to the study as developed methodologies, such as grounded theorizing and content analysis, have not been used to analyse and determine the importance of the information, thus the findings must be treated as descriptive rather than as a formal theory. Instead, to minimise this limitation, the author has relied upon highly cited journal publications to ground the framework.

Finally limitations regarding the content analysis described in section 3 are discussed. The search method used in this study has been conducted in a systematic but rigid manner. Although this presents an explicit and transparent approach of searching for literature, it is possible that papers which are of value to this study were not found as they fall outside of the keyword search criteria or are not present within the databases used. Another limitation occurs during the review of the coded results as only a single person has been used. This reduces the validity of the content analysis as only using a single person may unintentionally bias results based upon their interpretations and preconceived ideas.

3.5 Chapter 3 Summary

Within this chapter a content analysis has been conducted to identify and then evaluate decision tools and methods. Using a systematic search process from three established bibliographic databases, 41 relevant publications were found. The publications were then evaluated against a set of decision requirements established within a framework of the problem in section 2.

Based upon the findings from this analysis the following conclusions have been drawn which can used as research avenues for future work;

- The impact of uncertain factors upon the decision objectives is limited. Future tools should allow decision makers to assess the risk associated of these uncertainties.
- Factors that may affect the decision objectives are usually looked at in isolation within the tactical and operational phases. More work could be conducted to integrate the effects of these factors.
- Whilst cost and environmental objectives have generally received a good level of attention from the decision tools, few tools assess the time, quality and social criteria.

4 Support Tool Specification

This chapter focuses the scope of the research to develop a support tool to estimate the cost of remanufacturing a product, based upon the findings from the previous two chapters. The rational for focusing upon this particular topic is discussed, before the precise requirements for a support tool to assist remanufacturing feasibility assessment are defined.

4.1 Chapter 4 Introduction

Within Chapter 2 an understanding of the assessment of remanufacturing feasibility was developed through a literature review and findings from high level industrial case studies. Chapter 3 was then used to specifically identify and review the tools designed to assist with this decision process, based upon the key findings of Chapter 2. The purpose of this chapter is to narrow the focus of the research scope to a particular application, then, utilising the knowledge gained from Chapters 2 and 3, propose a specific requirements specification for a support tool which is to be developed. This specification will then be used as a brief for the stage 2 of this thesis (Chapters 5 -7) for the design and implementation of a tool and a means of evaluation and testing.

The remainder of the chapter is as follows: Firstly the research scope is narrowed to a particular objective and the rationale for this decision is discussed. Next a brief overview of how this PhD research contributed toward the PREMANUS research project is discussed and what implications this has had upon the implementation of the software tool. Finally a requirements and specification document is outlined for the development of the tool.

4.2 Focusing of the Research Scope

Three potential research avenues for support tools assisting decision making were identified within the conclusions for Chapter 3. Although addressing all of these research challenges would be desirable, due to the time and resource constraints of this PhD, it is not possible to develop suitable tools to fulfil all of the outlined areas. Therefore the remainder of this research has focused upon one particular challenge. The criteria used to evaluate this decision included;

- Maximising the value of the research contributions
- Ensuring access to case studies for validation

Maximising the value of the research contribution is a primary driver behind the decision of which of research challenges to pursue. As identified within Chapter 3, all of the areas mentioned above present valid academic research contributions, however it is difficult to rank the importance of each purely from an academic perspective. Due to the industrial nature of this research, businesses conducting remanufacturing hold a key stake in determining the importance of the research. It was therefore decided to consult industry to discuss which of the challenges presented greatest benefit to their business. Finding businesses willing to participate in research can be difficult due to their time and resource constraints. Businesses tend to be more interested in research when their own goals are shared by the research in question. The author of this thesis had links to the PREMANUS project, a European ICT project developing services for remanufacturing businesses (further explanation of the project is given in section 4.2.1), which included two industrial partners. It was decided to use these industrial partners to help establish the particular research challenge to focus on, as they could also be used within the evaluation phase as case study examples. Discussions were held with the industrial partners to decide upon the specific research focus from those identified.

Of the potential research options identified, it became clear that the area of most value would be the ability to incorporate uncertain factors within their decision making, in particular when estimating the economic cost of remanufacture. It was decided that this would therefore be a suitable research topic to focus upon and could be used as a foundation to incorporate the additional research avenues in further work.

4.2.1 Overview of the PREMANUS Project

The decision of which research challenge to pursue was partially influenced by the involvement with the PREMANUS Project. The project was funded by the European Union's Seventh Framework Programme, with the aim '*to overcome the asymmetric distribution of information in the End of Life recovery of products by connecting OEMs and subcontractors, with a special emphasis on remanufacturing'* (PREMANUS:2013b). An aim of the project was to develop middleware based upon three technological pillars;

- Remanufacturing Information Service
- Remanufacturing Services Gateway
- Business Decision Support System (BDSS)

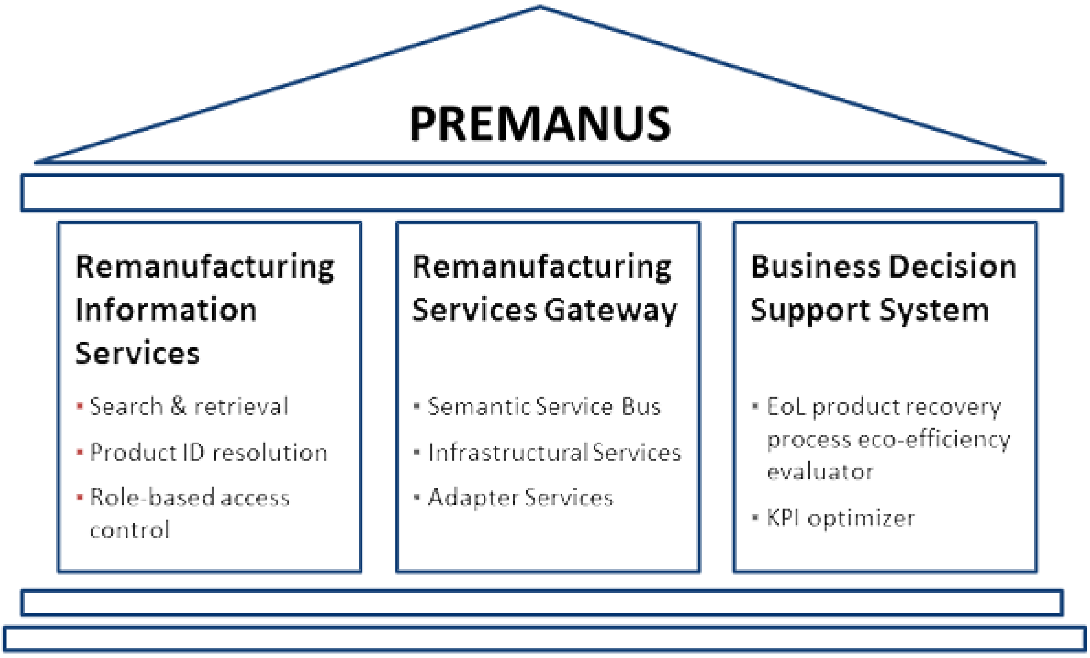


Figure 4-1 The three pillars of the PREMANUS middleware

The work conducted within this thesis contributed to an element of the BDSS section of the project. The project involved several partners from academic institutions, ICT technology companies and remanufacturing businesses. The two remanufacturing businesses were used to demonstrate and validate the developed support tool in Chapter 8.

4.3 Requirements and assumptions for the support tool

4.3.1 Introduction

The software requirements specification is outlined within this section. The purpose of this section is to formally document the scope of the support tool to be developed, with explicit references to the functionality and performance requirements. The specific requirements outlined within this section are to be used as the validation criteria to evaluate the tool within Chapter 8. This software requirements specification is based upon the IEEE standard 830-1998 *Recommended Practice for Software Requirements Specification (1998)*.

The tool to be developed will support the estimation of economic cost for a product to be remanufactured and also identify potential risks due to uncertainties within the remanufacturing process. The support tool developed will be referred to as the cost estimation tool for the rest of this thesis. The intended use of the cost estimation tool is within the operational phase of remanufacturing, to assess the viability of product remanufacture. It is designed to be used prior to the decision of whether to conduct remanufacture in order to generate an economic evaluation. Whilst some methods have been proposed (Jun et al.:2007) none address the information and process uncertainties present at this decision stage. The key benefits of this cost estimation tool therefore are that it not only generates a cost estimate, but also provides an understanding of the potential economic risks due to the uncertainties present, thus giving decision makers a richer understanding of the economic evaluation.

After this introduction the software requirements specification comprises of two sections. The first provides an overall description of the software tool requirements, including the key functionality and performance which is required and the justification. The second section provides an explicit list of each of the functional and performance requirements of the cost estimation tool.

4.3.2 Overall description

4.3.2.1 Cost Estimation Tool Functions

The functional requirements of the cost estimation tool are discussed here. Three key functional requirements are outlined and discussed;

- Estimate the economic cost of product remanufacture
- Provide economic risk metrics of the cost estimate when uncertainty is present
- Provide a generic tool solution that can be applied to multiple remanufacturing businesses

The first requirement is for the tool to estimate an economic cost for a product being remanufactured. This is an important factor within the decision of whether to remanufacture a product, as discussed within section 2.3.1.1. Due to the complexities of some of the products that are remanufactured, particularly those of high value which involve multiple sub components and assemblies, the task of conducting this economic product assessment can be large and time consuming. For this reason a tool that can provide reliable and transparent economic cost estimates was desired by the remanufacturing partners within the PREMANUS project. Due to the time constraints of this PhD research the decision was taken to limit the scenario of the cost estimate to the following;

- Remanufacturing is treated as a single job lot (i.e. a lot size a 1).
- The remanufacturing process begins as the product arrives at the factory and finishes upon its departure, i.e. logistical costs are not considered
- The cost of storage is not considered within the estimate

The second requirement is to provide economic risk metrics of the cost estimate when uncertainty is present. As discussed in section 3.4.4, many of the tools developed within academia have lacked the capability of incorporating uncertainties found within remanufacturing into their support tools. A key requirement of this work is therefore to ensure that uncertain features often found within remanufacturing, can be expressed within the cost estimation tool and their effects factored into the results. For the purpose of this tool three areas of uncertainty are to be considered;

- The product design

- The condition of the returned product
- The general process

Uncertainties related to a product’s design and condition are discussed in section 2.5. The additional uncertainty added to this list is those related to general process uncertainties. This is partially discussed within section 2.5 regarding the availability of historical cost information, but additionally refers to inherent process uncertainties, such as variable activity times.

The final requirement of the software tool is that it should be generic in its approach to enable cost estimation for a range of remanufacturers and products. As discussed throughout Chapter 2, remanufacturing is conducted by a diverse range of business types, from multinational OEM’s to small scale independents and over a range of different product types. It is an important part of the research to ensure that the software tool developed will enable the specific descriptions of the products and processes of particular businesses. This is an important part of this research as the final cost estimation tool should not be designed for only a single remanufacturing example, rather it should be useful to any remanufacturer wishing to undertake cost estimation of product remanufacture. The software tool must therefore provide a generic method for representing the following specific aspects of a estimation problem;

- Product
- Process
- Cost Information

The product and process are highlighted as key factors affecting the tactical and operational stage, as discussed in sections 2.4.2.2 and 2.4.3 respectively. The cost information requirement has been added to the specification due to the varying information management of individual businesses. The information recorded by businesses may vary, therefore the cost estimation tool should be flexible in accommodating the varying information types found in businesses.

4.3.2.2 User characteristics

Whilst the tool is intended for the operational phase, its intended users are operational and middle management. The tool does not give definitive answers to determine whether a product should be remanufactured, rather it provides the decision maker with relevant economic information, which can then be used in conjunction with other information to make a decision.

4.3.3 Specific requirements

Within Table 4-1 the specific requirements of the software tool are explicitly defined, along with their justification and if applicable, explanation of novelty or references to related literature. These requirements will be used later to evaluate the tool.

Table 4-1 Functional requirements list

Id	Description	Justification	Relevant tools and research
1.	**Cost Calculation** - The system will estimate the economic cost of remanufacturing a particular product under the following conditions; • Remanufacturing is treated as a single job lot (i.e. a lot size a 1). • The remanufacturing process begins as the product arrives at the factory and finishes upon its departure, i.e. logistical costs are not considered • The cost of storage is not considered within the estimate	Industry requires methods of calculating economic cost, particularly for complex products, where numerous activities and resources are required. Few methods of calculating the economic cost of product remanufacture are found within literature.	Chapter 3 highlighted a small number of specific cost calculation methods for remanufacturing, with the most complex being presented by Jun et al (2007) and Jun et al (2012), whilst simpler methods include Krill and Thurston (2005), and Du et al (2012). Many of these simple methods are used as part of larger process planning and scheduling optimisation problems rather than for individual product cost quotes.
2.	**Risk and Uncertainty** - The system will estimate the economic risk of remanufacturing a particular product due to the following uncertainties;	The added complexity of remanufacturing cost estimation is the numerous sources of uncertainty present.	None of the specific remanufacturing cost estimation techniques identified in Chapter 3 enable uncertainty to be expressed and risk to be assessed.
2.1. 2.1.1.	**Product Design** – The system will allow calculation of cost when uncertainties regarding the product design are present. The uncertainties refer to the following specific product design aspects; *Key Attributes* – When key attribute information, such as product weight, is unknown. *Structural Layout (BoM)* – When the number and type of components making up the product are unknown.	Many products that are considered for remanufacturer may contain missing or incomplete information which will affect the ability to perform detailed economic cost estimation. This is particularly prevalent for independent remanufacturers, as explained in section 2.5.	Linguistic techniques have been used to describe product features when uncertainty and ambiguity exist (Gehin et al.:2008, Xing, Luong:2009, Ghazalli, Murata:2011). However, it should be noted that these are used in direct economic cost estimation.
2.2. 2.2.1. 2.2.2.	**Product Condition** – The system will allow calculation of cost when uncertainties regarding the product condition are present. The uncertainties refer to the following specific types; *Unknown Condition* – When no information exists regarding the information of the product condition. *Ambiguous condition* - When information related to the product condition does not always correlate to an exact process outcome.	Many products will be considered for remanufacturer with little or no information regarding its physical condition, discussed in section 2.5. Information used to describe the product condition does not always correlate to an exact remanufacturing outcome.	Uncertain product condition has been modelled using stochastic methods for the purpose of process planning (Xanthopoulos, Iakovou:2009), however this is to monitor the effects on high volume remanufacturing rather than the implications on individual product cost calculation.
2.3. 2.3.1. 2.3.2.	**Process –** The system will account for uncertainties related to the remanufacturing process within the cost estimation for the following factors; *Inherent process variations* – Where inherent variations may occur from one process to another when all other given factors are equal, such as disassembly time. *Process knowledge uncertainties* – When information about specific remanufacturing activities is unknown due to a lack of experience.	Whilst many of the remanufacturing process uncertainties stem from the product and its condition, there still are inherent uncertainties stemming from the process itself.	None of the costing examples found within remanufacturing treat aspects of the remanufacturing process and its activities, such as resource consumption as uncertain.

3.	**Generic Functionality** – The system will be robust to ensure that a generic remanufacturer can use the tool specifically for their application. In order to comply with this requirement, the following specific sub elements have been outlined;	In order for the tool to be truly suitable for remanufacturing, it must be generic and robust to suit the diverse range of business conducting remanufacturing activities.	Within the remanufacturing costing techniques identified, limited details regarding their information models and requirements have been published. Related research away from the cost estimation domain is described below.
3.1. 3.1.1. 3.1.2.	**Product Design** – The system will provide a generic product model, in which specific products can be described. Explicitly it is comprised of the following requirements; *Product Types* – The product model will allow for multiple types of product and component to be described. It should allow for specific attributes which may be unique to particular products to be described. *Variations within product types* – The product model shall also allow variations between products types to be described, such as the number and type of components that it may contain.	Remanufacturing takes place on a variety of different products. Each product is comprised of various attributes which can be uniquely be used to identify remanufacturing costs. It is important the software system is robust enough to ensure that multiple products and components can be described adequately.	Product information models suitable for capturing information requirements for EoL have been proposed by Um et al. (2008) and QLM data model (The Open Group QLM Work Group:2012).
3.2.	**Process Design** – The system will provide a generic process information model, in which specific remanufacturing process can be described. The process shall allow the generic remanufacturing activities to be described, as shown in section 2.3.2.1. The process should allow the possible permutations that may occur to be described.	Each business will use their custom process to remanufacturer a product. Whilst similarities will be shared between process stages, as described in section 2.3.2.1, the cost estimation should be robust enough to allow for a business to describe their specific remanufacturing process and estimates its cost.	Specific information models to satisfy the requirements of remanufacturing processes have received limited research. Ijomah and Childe (2007) use IDEF0 to model a generic remanufacturing business process, although its use to assist cost estimation is unknown. Additionally Zor et al (2011) investigate the extension of Business Process Model and Notation (BPMN) for describing manufacturing processes.
3.3.	**Cost information –** The system shall enable cost information from multiple sources to be used.	Cost information may be contained within various sources, such as human experts, internal databases and external databases. This information may also be recorded in different formats depending upon the businesses accounting methods.	This requirement in itself is not novel however its implementation within remanufacturing cost estimations will be.

5 Cost and Risk Calculation Techniques

Chapter 4 identified the specific research aim of developing a tool to assist remanufacturing feasibility assessment which calculates the cost of remanufacturing a product and expresses the uncertainty within the estimate. This chapter assesses the literature specifically related to cost estimation and uncertainty to identify methods which would be suitable for the remanufacturing domain.

5.1 Chapter 5 Introduction

Within Chapter 3 a review of the tools and methods aimed to assist with the decision of assessing of remanufacturing viability was conducted. One of the findings was a lack of tools and methods able to provide cost estimates which factored in the uncertainties present within remanufacturing, such as the returned product condition. Within the Chapter 4 it was decided to pursue this area and develop a suitable tool to meet the cost requirements of remanufacturing.

In order to develop a suitable tool for this application, an understanding of methods and techniques used to predict cost and measure risk are required. The aim of this chapter is therefore, *to develop an understanding of the methods and techniques used to produce cost and risk estimation within other domains, and determine their suitability to the application of operational remanufacturing*.

In order to meet this aim, four specific objectives have been outlined which are;

5-1. Identify the generic elements of a cost estimation
5-2. Identify methods and techniques used to estimate cost
5-3. Identify methods to incorporate uncertainty and risk
5-4. Determine how applicable the identified cost and risk methods are to the remanufacturing problem?

The remainder of the chapter is laid out as follows: A methodology is presented in section 5.2 explaining the method used to meet these objectives through a literature search. In section 5.3 findings from the literature search are presented, identifying generic cost estimation elements, methods, as well as the techniques used to enable uncertain inputs and risk to be measured. Within section 5.4 a discussion is conducted assessing how applicable these methods and techniques are to the remanufacturing problem. Finally section 5.5 presents the conclusions, summarising the work done, findings and implications of this chapter.

5.2 Method for Identifying Cost and Risk Techniques

To meet objectives 5-1 to 5-3 a literature search is conducted to identify work conducted in the area of cost estimation with uncertainty and risk. However, due to the wide range of domains this research area encompasses, the search space is quite large. Therefore, to conduct the literature search, the highly established bibliographic search engines Scopus, Compendex and Web of Science were used to identify publications, due to their wide inclusion of domain areas. Publications have been limited to journal published literature reviews, as it is believed these will yield the most well defined methods and techniques. A structured keyword search was used to identify papers. The term “cost estimation” was used to search for relevant papers. Within Scopus and Web of Science an option to limit papers to just reviews was selected, however this was not present in Compendex so the term “Review” was added to the search terms, with the results for each shown in Table 5-1.

Table 5-1 Details and results from database search for cost estimation review publications

Keyword Search Terms	Results		
	Scopus	**Compendex**	**Web of Science**
“Cost Estimation”	74	N/A	73
“Cost Estimation” & Review	N/A	79	N/A

Titles and abstracts were then manually assessed to remove duplications and irrelevant studies. A total of 19 publications were found to be useful for this research, shown in Table 5-2.

Table 5-2 Publications used within this study for cost estimation techniques

Publication Reference	Domain Area	Number of Citations
Van Genuchten and Koolen (1991)	Software	35
Boehm et al. (2000)	Software	99
Ali (2005)	Construction	2
Doshi et al. (2006)	Medical	37
Niazi et al. (2006)	Product Cost Estimation	96
Jørgensen and Shepperd (2007)	Software Development	268
Kitchenham et al. (2007)	Software	109
Goh et al (2009)	Service Contracts	13
García-Crespo et al. (2011)	Machine Part Manufacturing	2
Datta and Roy (2010)	Service Support Contract	17
Petroutsatou and Lambropoulos (2010)	Construction	3
Fukuda et al. (2011)	Medical	8
Liao et al. (2011)	Construction	13
Roy et al. (2011)	Automotive	5
Huang et al. (2012)	Service Costing	0
Parthan et al. (2012)	Waste Management	6
Trivailo et al. (2012)	Space Mission Planning	4
Yeh and Deng (2012)	Product Life Cycle	1
Smith and Rudmik (2013)	Health	0

The publications were then analysed and compared to identify;

- The main elements of a cost estimation
- The main general methods of cost estimation
- Specific cost estimation techniques
- Methods and techniques used to deal with uncertainty

The findings and results of the literature search are then shown in section 5.3.

To fulfil objective 5-4, an understanding of the requirements for cost estimation within the operational remanufacturing domain is required. This is obtained using the same methods described in Chapter 2. The requirements are then presented in the format of the main cost estimation elements identified in objective 5-1. These requirements are then compared to the methods and techniques discovered within objectives 5-2 and 5-3 to determine suitable approaches to cost estimation for operational level remanufacturing.

5.3 Findings from Cost and Risk Literature

5.3.1 Generic Cost Estimation Structure and Elements

Cost estimation is a common requirement within decision making across many domains. However, the approach used to generate the estimation may differ significantly depending upon the application, requirements and constraints. In order to determine why different approaches are used, an understanding of the key features of a cost estimate is required. Based upon the literature findings, a common structure for cost estimation has been developed which is then used as a basis for the conceptual design, shown in Figure 5-1. The key elements and features of this structure are described below;

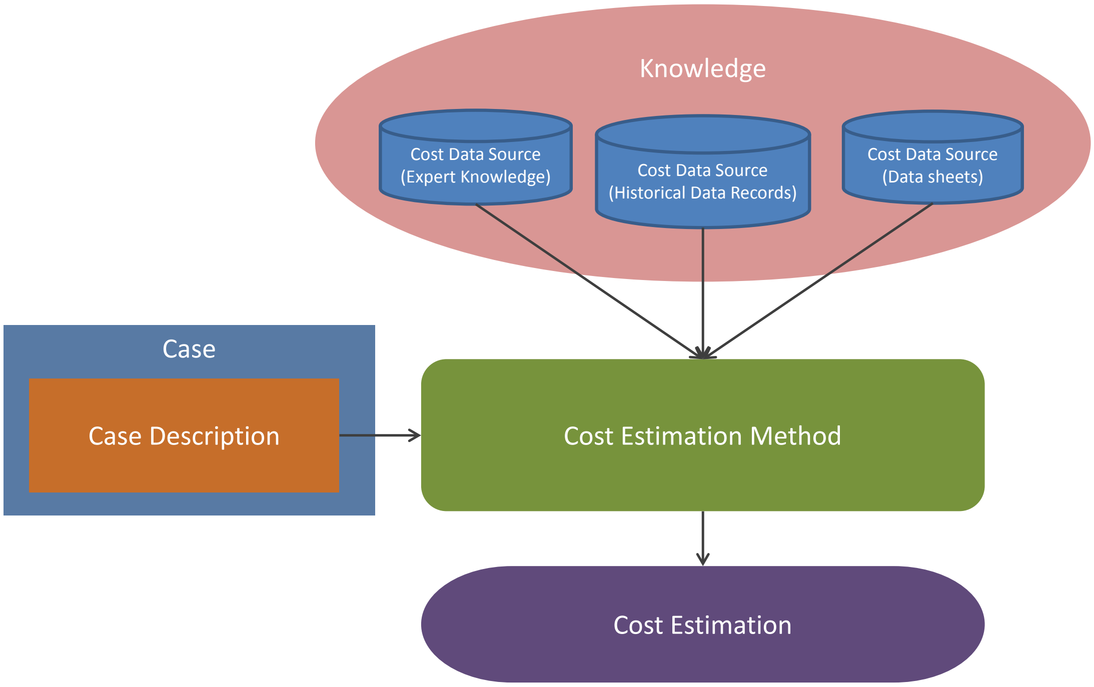


Figure 5-1 Conceptual design of the generic elements found within a cost estimation tool

5.3.1.1 Case

The case is the actual future event for which the cost estimation is being conducted. It is represented within the cost estimation through the Case Description (see below). Common examples include a construction project (Petroutsatou, Lambropoulos:2010), software development (Jørgensen, Shepperd:2007) and product manufacturing cost.

5.3.1.2 Case Description

The case description is the information used to describe a particular case for which estimation is required. It is required to allow users to input, edit or vary the specific details about a particular case for which the cost is being estimated. The level of definition used within the case description often depends upon the stage at which the estimation is taking place (Sabol:2008), with Trivailo et al. (2012) highlighting the link between the stage at which the estimation takes place (e.g. feasibility and production) and the level of uncertainty. When cost estimates are designed as early estimates for feasibility analysis, the case description will be less detailed than for estimations near production.

Careful design of information models are required for the case description, to ensure that the information captured is relevant, robust and available, particularly when a tool is designed to be used multiple times for a range of unique cost estimations. The type of information used for the case description will be linked to the cost estimation methodology. Specific attributes related to the case are described either quantitatively or qualitatively and are then used by the cost estimation method to generate a prediction. It is impossible to describe every detail about the actual case scenario in question so there will inevitably be some detail and information missing.

5.3.1.3 Knowledge Base

The knowledge base is the understanding of the problem area, which is drawn upon to produce the cost estimate. Based upon the authors’ understanding, three general types of data source can be used to extract information and knowledge; expert knowledge, historical records, and data sheets.

Expert knowledge is human understanding about the costing area. This is not usually formally documented and will therefore require extracting using interviews or techniques such as the Delphi Method (Trivailo et al.:2012, Boehm et al.:2000, Goh et al.:2009). It can then be stored in the form of rules, decision tress, heuristics (Niazi et al.:2006), ready for recall by estimation method. Expert knowledge is widely used as information source for cost estimates (Van Genuchten, Koolen:1991), however is often criticised as a source of inaccuracy due to being prone to bias and error (Datta, Roy:2010).

Historical records are tangible information which has been recorded about previous cases (Van Genuchten, Koolen:1991). They can contain information about the previous case description, such as key attributes, and also outcomes about the actual case, such as resources used and their costs. These can exist in a number of forms such as accounting records, contracts, cost reports and historical and technical databases (Trivailo et al.:2012, Roy et al.:2011). This information can be utilised by analogical techniques, to identify similarities between the case description and historical examples, or by parametric techniques which aim to identify relationships and rules in the empirical data.

Finally cost data sheets give current information about known cost information, regarding raw materials or components from external sources, such as suppliers.

5.3.1.4 Cost Estimation Method

The cost estimation method is the process or technique used to generate the cost estimate (Niazi et al.:2006). The method uses the case description and processes relevant information from the knowledge base to generate the cost estimate. Different methods are discussed in section 5.3.2.1. The implementation of a method is referred to as a cost estimation technique within this Thesis. A number of specific techniques have been used to implement the estimation method, which are discussed in section 5.3.2.2.

5.3.1.5 Cost Estimation

The cost estimation is the resulting output from the cost estimation method. This is used to convey the estimate to the user who can then use the information to assist with a particular decision. Whilst in many cases the result is a single point estimate which provides purely a overall cost, others may provide further detail such as breakdown of cost activities and resources required, or additional metrics to convey the uncertainty and risk, such as a three point estimate or cost distribution (Hull:1992).

5.3.1.6 Additional Factors

The elements described above explain the key features of the cost tool. However there are additional factors which can affect the decision of which specific cost estimation method is used, including the resources available to develop the cost tool and the uncertainty of the information used.

In order to generate a cost estimate resources are required to form the case description, collate and extract information from the knowledge base, set up the cost method and finally execute the cost estimation. The amount of resource available will act as a constraint to which cost estimation method is adopted.

Within any cost estimation there will inherently be some form of uncertainty. Uncertainty can be found within the case description and the knowledge base. Uncertainty within the case description occurs when there is either a lack of user understanding or inherent randomness regarding the case. For example, within the conceptual design stage of a project there will be large uncertainty regarding specific details required to complete the task. As the project develops, these uncertainties will reduce as the specific details of the tasks required become clearer. Uncertainty is discussed in greater depth within section 5.3.3.

5.3.2 Cost Estimation Methods

5.3.2.1 General Methods

The cost estimation method is the process used to evaluate the case description and utilise the knowledge base to generate the cost estimate. A universal classification of cost estimation methods was not directly found within the literature, with several different classifications presented. However, it was possible to identify four distinct methodologies that commonly occurred: intuitive, analogical, parametric and analytic. These methods are summarised in Table 5-3.

Table 5-3 Summary of cost estimation techniques

Cost Estimation Method	**Bottom up or top down?**	**Data Source**	**Advantage**	**Limitation**
Intuitive	Top down	Expert knowledge	Quick to produce and flexible, can be just as accurate as more expensive techniques	Subjective and prone to human bias
Analogical	Top down	Historical case data	Does not require a large data set	Limited to how close the historical data matches the current case
Parametric	Top down	Historical case data	Fast to compute, requires little information within the case description	Problem can be oversimplified, relies upon strong knowledge base to extract relationships
Analytical	Bottom up	Mixed	Most accurate	Resource intensive, slow execution, detailed data may not be available

Each method differs through their use of different knowledge sources and their requirements from the case description, resources required and overall accuracy. Each method is now discussed in greater detail below;

5.3.2.1.1 Intuitive

Intuitive methods, also referred to as expert judgment (Trivailo et al.:2012) or expertise-based (Boehm et al.:2000), make use of expert experience to form cost estimates. These involve consulting with one or more experts to generate the cost estimation (Van Genuchten, Koolen:1991). The knowledge and rules extracted can be captured and stored within applications such as decision support systems, making the cost estimation reusable for future case scenarios. Intuitive methods are particularly useful in the absence of quantitative and empirical data (Boehm et al.:2000), can require fewer resources and time to execute than other methods, and in certain circumstances, can be just as accurate as more expensive methods (Datta, Roy:2010). For these reasons this method has been cited as one of the widely used within cost estimation (Roy et al.:2011). However, the major drawback of this method is that the expert knowledge is subjective, therefore the accuracy of each estimate is uncertain. This approach is therefore useful in situations where historical recorded data is scarce or unavailable (Trivailo et al.:2012).

5.3.2.1.2 Analogical

Analogical methods utilise historical data records to generate a cost estimate. They identify similarities between historical cases and the new case which is being estimated. Costs are then extrapolated to fit the new case. Although similar to intuitive methods, the key difference is that analogy uses recorded facts about previous case scenarios (Van Genuchten, Koolen:1991). Analogical techniques are particularly useful when attempting cost estimation where understandings of cost driver relationships are not well known. These require relatively few resources to execute as only a simple case description is required.

Analogical methods are limited however to the quality of the historical records and their similarity to the new case. Common analogical techniques include regression analysis and back propagation neural networks (Niazi et al.:2006, García-Crespo et al.:2011, Huang et al.:2012, Datta, Roy:2010). García-Crespo et al. (2011) also note that case-based reasoning has also been included within this category by other authors.

5.3.2.1.3 Parametric

Parametric methods use quantitative models to express the relationship between key attributes that affect cost, sometimes referred to as cost drivers (Niazi et al.:2006). These methods can simplify the cost estimation problem, enabling a simple case description to be used and thus reducing time and resources required to execute the cost estimation. To describe these relationships a large knowledge base is required, usually through analysis of statistical case records, or sometimes through expert knowledge. However, it can be difficult to include all cost relationships within a single parametric equation, thus they are susceptible to errors for complex costing problems where relationships are difficult to identify.

5.3.2.1.4 Analytical

Analytical techniques (also described as bottom up methods (Trivailo et al.:2012, Datta, Roy:2010)) are the most detailed of all the cost estimates methods discussed. The cost estimate is decomposed into its constitutional elements which are then summed together to generate the total cost (Niazi et al.:2006). There are several methods of doing this such as operational, feature, breakdown, tolerance and activity based (Niazi et al.:2006). Due to the level of detail required within the estimate, the results tend to be the most accurate of those already discussed. However, these methods are regarded as resource intensive due to the large amount of information required to describe the case and they are more suitable to the later stages of cost estimation where this information is readily available (Trivailo et al.:2012).

5.3.2.2 Estimation Techniques

A number of techniques for implementing cost estimation methods have been discussed within the literature review articles. It is beyond the scope of this chapter to provide a detailed account of each specific technique found, so instead the most common types will be reviewed. An overview of each technique is given and summarised in Table 5-4, along with their benefits and limitations.

Table 5-4 Summary of cost estimation techniques

Technique	Estimation Method	Advantages	Limitations
Case Based Reasoning	Analogical/Intuitive	Reduction of the knowledge acquisition, useful in domains with small body of knowledge, works with incomplete or imprecise data	Accuracy limited to the closeness of previous cases
Decision Support Systems	Intuitive	Simple heuristics can guide the user to the most appropriate estimation method and data	Rule encapsulation can be time consuming
Regression Analysis	Analogical/Parametric	Can provide simple and powerful relationships between cost and identified variables	Requires large data sets,
Artificial Neural Networks	Analogical	Non-linear, requires less data than statistical methods.	Data sets are required, little insight to the analysis is provided

5.3.2.2.1 Case-Based Reasoning

Cased-based reasoning (CBR) is a technique which utilises both analogical and intuitive methods to generate the cost estimate. It retrieves historical case examples suitable to the new target case by identifying similar features and attributes. When an exact match is not found case adaption is used to modify the historical case to suit that of the target (Pal, Shiu:2004). Expert judgment is used to signify the importance of features and attributes to the overall cost through weightings.

Advantages of using CBR include;

- Reduction of the knowledge acquisition task, meaning that rules and models are not required to be extracted from the knowledge base, reducing development time and resource (Pal, Shiu:2004).
- Enable reasoning and estimation in domains that are not fully understood or where only a small body of knowledge is present (Pal, Shiu:2004).
- Reasoning with incomplete or imprecise data (Pal, Shiu:2004).

Limitations of CBR include;

- Accuracy of estimation will depend upon how close past cases are to the new case

Examples of uses of CBR systems in other domains include retrieving preceding law cases for legal arguments, determining house prices based on similar information and forecasting weather conditions (Pal, Shiu:2004).

5.3.2.2.2 Decision Support Systems

A Decision Support System (DSS) encapsulates rules and expert knowledge regarding a costing problem. By entering information into the system regarding the target case, the rules held within the system can guide the user to the most appropriate costing solution, such as a particular parametric equation. DSS are classified by Niazi et al (2006) as an intuitive system due to the logic dictating the rules usually being heuristics. They do not provide answers to structured problems, rather, they emphasize direct support for decision makers in order to enhance the professional judgments required in their decision making (Nelson Ford:1985). Several classifications of DSS exist including rule based and expert systems (Niazi et al.:2006).

Advantages;

- Simple heuristics can guide the user to an appropriate cost method

Limitations;

- Can be time consuming to encapsulate rules (Niazi et al.:2006)

Examples of DSS being utilized within cost estimation include Shehab and Abdalla (2002) who developed a knowledge based system to support product cost estimation at the conceptual design phase

5.3.2.2.3 Artificial Neural Networks

Artificial Neural Networks (ANN) are computer programs designed to simulate the way the human brain processes information (Agatonovic-Kustrin, Beresford:2000). The network is presented as a system of interconnected neurons, also known as processing elements, which can take in multiple weighted inputs, perform simple information processing and deliver an output. The power of the ANN comes from the connecting neurons in a network (Agatonovic-Kustrin, Beresford:2000). Common structures of ANN include recurrent and feedforward networks. Detailed explanation of each of these network designs are out of the scope of this chapter, but further information can be found from Maier and Dandy (1998). Once a network has been structured it must then be trained. Training involves optimising the network to minimise the error between model outputs and corresponding historical values (Maier, Dandy:1998).There are many forms of training, however the most common is the back-propagation algorithm (Agatonovic-Kustrin, Beresford:2000, Maier, Dandy:1998). As ANN's are trained using historical data they can be classified within the analogical cost estimation methods (Niazi et al.:2006).

Advantages;

- Relatively insensitive to data noise (Maier, Dandy:1998)
- Perform reasonably well when limited data is available (Maier, Dandy:1998)

Limitations;

- Black box approach with little insight into the analysis process (Shtub, Zimerman:1993)

Examples of the use of ANN within cost estimation include the early phases of building design (Murat Günaydın, Zeynep Doğan:2004), product packaging (Zhang, Fuh:1998) and software cost estimation (Idri et al.:2002).

5.3.2.2.4 Regression Analysis

Regression analysis is a statistical process in which relationships can be established between costs and variables of past cases (Niazi et al.:2006). The process can be thought of as both analogical and parametric (García-Crespo et al.:2011), as it identifies relationships from statistical data sets in order to generate equations for estimates to be calculated. Regression analysis covers a range of specific statistical techniques which include linear regression, ordinary least squares and polynomial regression.

Once a regression model is constructed a diagnosis should be performed to determine the correlation to the actual data using fitness techniques such as the R-Squared method.

Advantages

- Can allow simple cost estimation based on a few input parameters to describe the case

Limitations

- Requires a large data set to develop relationships
- Difficult to estimate complex problems where multiple non-linear parameters are present

5.3.3 Uncertainty

5.3.3.1 Types of uncertainty within Cost Estimates

Due to the nature of cost estimations being a prediction of future events, there will inevitably be some form of associated uncertainty. Uncertainty can be defined as a deficiency in the knowledge which may cause predictions to differ from that of reality (Goh et al.:2009). Uncertainty can be categorised into two distinct groups, epistemic and aleatory (Erkoyuncu et al.:2011). Epistemic refers to uncertainty that is caused by a lack of human knowledge or understanding. It can be reduced through an increased understanding or data. Aleatory uncertainty refers to inherent uncertainty, where, even with increased data and understanding, uncertainties will remain, such as gambling.

Goh et al (2009) highlights three key areas where uncertainty can occur within the cost estimate: data (knowledge base), model (cost estimation method) and the case scenario (case description). Data uncertainty can occur both within the case description and the knowledge base of the cost estimation. Data uncertainty may occur when the information required is unknown. A summary of data uncertainty types can be found in Table 5-5.

Table 5-5 Summary of data uncertainty (adapted from (Goh et al.:2009))

Data Uncertainty	Source	Type	Example
Variability	Inherent randomness	Aleatory	Repair time, mean time between failure
Statistical error	Lack of data	Epistemic	Scarce reliability data
Vagueness	Linguistic uncertainty	Epistemic	The component needs to be replaced about every 2 to 3 months
Ambiguity	Multiple sources of data	Epistemic	Expert 1 and expert 2 provide different values to end-of-life costs
Subjective judgment	Optimism bias	Epistemic	Over confidence in schedule allocation
Imprecision	Future decision or choice	Epistemic	Supplier A or B

As well as uncertainty within the data inputs, it can also occur within the cost estimation method itself through a lack of definition, assumptions or approximation, selection of cost estimation method, and complexity and correlation between cost elements (Goh et al.:2009).

Uncertainty in the case scenario stems from the inherent uncertainty of the case. This largely affects cost estimates for the long term where future decisions can be affected by factors such as new technologies, legislation changes, and supply chain disruption (Goh et al.:2009).

5.3.3.2 Modelling Uncertainty

Probability theory is a common approach used to model uncertainty within cost estimation (Goh et al.:2009). It uses Probability Density Functions (PDF) to describe the variability within a parameter, thus it is particularly useful when modelling aleatory uncertainty (Goh et al.:2009, Bae et al.:2004, Boussabaine, Kirkham:2004), such as failure time. The PDFs can be derived through either statistical methods if the data exists, or through subjective methods, such as expert opinion. The most common types of PDF are normal or triangular distribution (Datta, Roy:2010), but more complex PDFs can be used to describe particular distributions including beta, Pareto, Weibull, gamma, exponential and lognormal (Boussabaine, Kirkham:2004). When selecting PDFs with an accompanying data set, validation methods can be used such as the Chi-Square, Kolmgorov-Smirnov and Anderson-Darling tests (Boussabaine, Kirkham:2004), which enable the goodness of fit to be quantified.

A popular method of computing estimates with PDF inputs is through Monte Carlo Simulation. Monte Carlo simulation makes use of random number generators to derive values from the PDFs. Repeating the calculation through multiple “what if” scenarios enables the propagation of multiple uncertainties to be calculated (Goh et al.:2009). Results can be visualised using histograms to show the likelihood of a particular cost being incurred. Whilst probability theory is a popular method of modelling uncertainty, it is limited in its ability to treat all uncertainty as aleatory (Boussabaine, Kirkham:2004, Goh et al.:2009).

Fuzzy set theory is another method of expressing uncertainty within a cost estimate and is particularly useful when data is limited, vague, ambiguous or imprecise (Goh et al.:2009), such as found with epistemic uncertainty. Unlike classical set theory, in which an element membership is bivalent (0 or 1), fuzzy sets allow elements to have degrees of membership, thus enabling elements to have partial membership to multiple sets (Zimmermann:2010). This can enable uncertainty to be expressed by vague inputs such as linguistic expressions. For example, time to conduct an activity could be expressed as ‘short’, ‘medium’, or ‘long’, with each linguistic value classified as a fuzzy set and a quantitative measure of time represented with a membership function.

5.4 Remanufacturing Requirements

Within section 5.3 an understanding of the cost estimation problem is developed, with the key elements and components outlined and the methods and techniques used to generate the cost estimation and deal with uncertainty described. The specific requirements of cost estimation for remanufacturing are now presented using the structure of the cost estimation problem described in section 5.3.1. Potential solutions are then discussed within section 5.4.2.

5.4.1 Remanufacturing Description

The requirements for the cost estimation model are proposed in Chapter 4. The implications of these requirements upon the elements of the cost estimation model are now discussed and summarised in Table 5-6.

Table 5-6 summary of the specific requirements for a generic remanufacturing cost estimation system

Case	Can broadly be split into the remanufacturing process and the product to be remanufactured.
Case Description	Product description contains greatest uncertainty mainly surrounding its returned condition. Process description is relatively clear, however the exact activities are flexible to adaptation to the requirements of the product, therefore uncertainty in the process is inherently linked to the product
Knowledge Base	Not specific to remanufacturing and will vary depending upon the experience, ICT infrastructure, relationship with OEM and other suppliers.
Cost Estimation Method	See section 5.4.2
Cost Estimation	Express cost and risk. Also enable user to interrogate cost to understand how overall estimate is formed.
Resource	Variable
Uncertainty	Prevalent particularly within the product case description

5.4.1.1 Case

The case for which the cost estimation is being conducted is of the remanufacturing process being applied to a particular product in order to return it to an ‘as new’ quality. The key elements to the case are therefore the remanufacturing process and the product to be remanufactured.

5.4.1.2 Case Description

The case description will comprise of a representation of the product and the details of the remanufacturing process. The case description will naturally not be able to contain all of the information of the actual case. The specific details of each are now discussed further;

- The process is well understood as the remanufacturer knows their own capability regarding what can and cannot be remanufactured, and what activities they can conduct. However the exact set of activities used will be unknown if there is uncertainty in the product description.
- The ability to describe the product will vary between remanufacturers. OEMs or licensed third parties will tend to have greater understanding of the product type and construction than a third party, through access to detailed design records. The information about Middle of Life (MoL) will also vary depending upon the communication the product and remanufacturer. Where technologies such as condition monitoring have been employed, information regarding the MoL can be collected and analysed to predict the condition in which the product is returned, therefore enabling the case description to closer resemble the case. However, many products will not have access to these technologies, thus MoL information may be limited to more simple measurements such as engine odometer reading or a visual inspection. This variability in the type of information present requires a robust case description which can deal with varying data types.

5.4.1.3 Knowledge Base

The size and type of the knowledge base will vary between remanufacturers. Although remanufacturers may deal with a core set of products in which a strong data set may be built to conduct statistical analysis, new or rarer product types will always be encountered for which statistical analysis will not be viable. Therefore methods to derive cost estimations should be robust enough to deal with multiple knowledge sources.

5.4.1.4 Cost Estimation

The aim of the cost estimation is to inform the customer of the anticipated cost to remanufacture a particular product and also express the degree of uncertainty associated with the estimate. Whilst it is not required to produce perfect estimations, due to the inherent uncertainty, the tool should, where possible, provide transparent estimations that give the user an understanding of cost breakdowns and calculation methods, as a way of building user confidence in the tool.

5.4.1.5 Resource

The resources available to generate the cost estimate will vary between each remanufacturer. Any generic solution should be robust enough to suit small scale resource but be expandable to allow greater detail if available.

5.4.1.6 Uncertainty

Uncertainty is a key feature present to some extent within all remanufacturing businesses. The main source of uncertainty stems from the limited understanding of product to be remanufactured. This limits the ability to accurately describe the remanufacturing process, as the exact activities required to complete remanufacture will be unknown until a full understanding of the product requirements are known. Uncertainty can also be found within the knowledge base, as described by Goh et al. (2009). Whilst uncertainty may also occur here it is not a remanufacturing specific issue. An overview of uncertainty within remanufacturing is shown in Table 5-7. The system to be developed must therefore be able to incorporate uncertainty into the cost estimate.

Table 5-7 Uncertainty within remanufacturing

Case Description		**Knowledge Base**		
Product	**Process**	**Expert Opinion**	**Historical Data**	**Cost Data**
• Product Type • Product Condition	• Activities required • Activity variability	• Incomplete knowledge • Human bias	• Incomplete knowledge	• Material and component costs

5.4.2 Discussion

Whilst some commonality can be found within the requirements for remanufacturing, there is also a great deal of variability which needs to accounted for within any generic cost estimation solution. The discussion below addresses objective 5-4 by determining the most appropriate solution for the cost estimation method.

Which cost estimation approach to use?

With the aid of the decision making model in Figure 5-2, an understanding of the most suitable cost estimation method can be conducted. As the cost estimation is conducted at the operational stage, not the conceptual stage, a good understanding of the remanufacturing process is known. Using the decision model in Figure 5-2 either a parametric or analytical methodology would suit this type of cost estimation. However, due to the complexity of the remanufacturing problem, and the variability found within the knowledge base of remanufacturers, it is difficult to form parametric relationships. Therefore, an analytical method would appear to be the most suitable cost estimation technique.

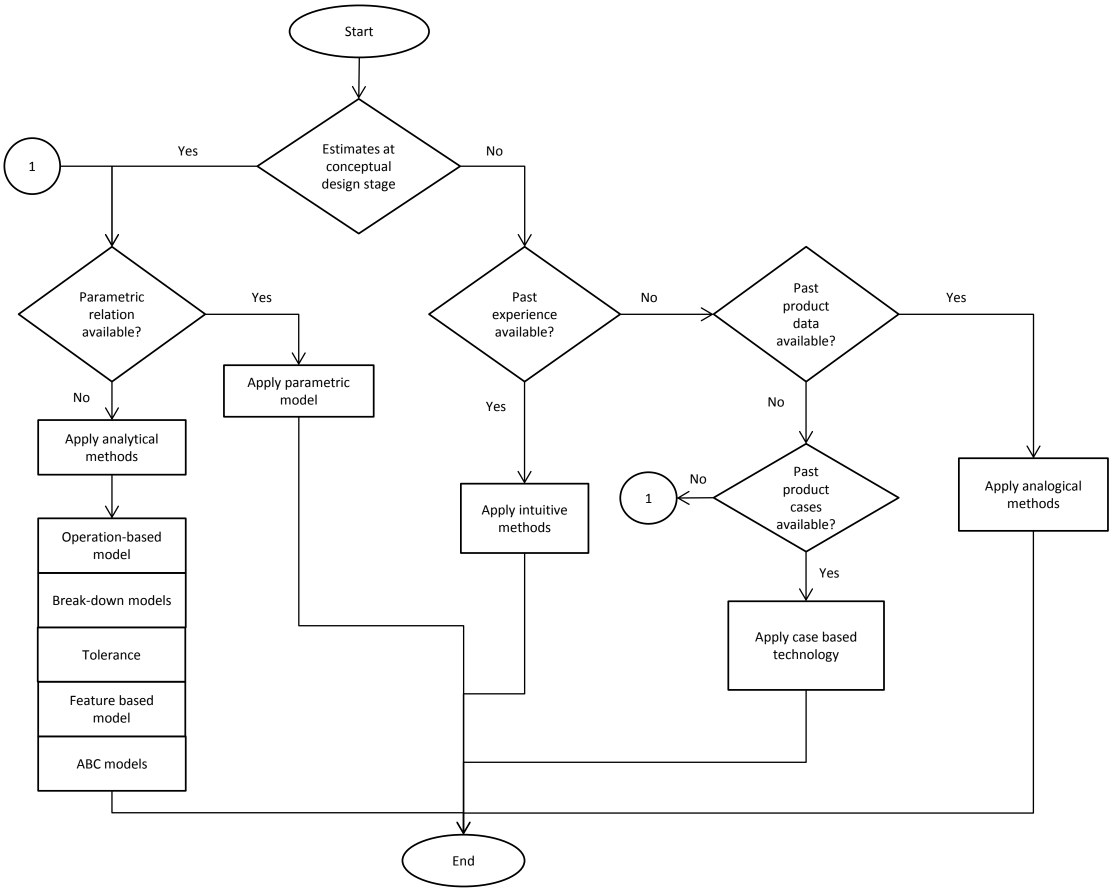


Figure 5-2 Adapted decision model developed by Niazi et al (2006) to determine suitable cost estimation method

Which specific techniques are most suitable?

Several different techniques have been identified to conduct analytic cost estimation including operational, breakdown, tolerance, feature based and activity based (Niazi et al.:2006). Of all of these the most appropriate for the remanufacturing domain are the breakdown and activity based cost approach. These are the most fitting mainly due to the distinct generic activities which make up remanufacturing (disassembly, inspection, cleaning, rework, assembly, testing), identified within section 2.3.2.1. Both tolerance and feature based costing techniques are difficult to apply to a remanufacturing scenario as they are intended for product design costing rather than a service based application, such as remanufacturing.

What about the process uncertainty?

Where the case description of the product is unknown, uncertainty about the process will be present. However, the rules determining why particular activities may be required are usually known, such as if the condition of the product is above or below a certain amount. By forming these rules it is possible to simulate the uncertainty of the remanufacturing process, using techniques such as the probability density functions, enabling the activity path to be determined.

How to generate a cost estimate for each activity?

Using either an activity or breakdown based costing approach enables the remanufacturing problem to be split into key activities, however cost estimation is still required for each of these. Determining the most appropriate cost estimation method for each activity is difficult due to the range of knowledge available. Therefore an appropriate solution is to enable multiple methods to be available to generate an activity cost. This creates a robust solution that is flexible to suit specific remanufacturing scenarios. However to dictate the most appropriate technique to apply for each particular activity a set of rules must be generated. This can be stored within a decision model such as shown in Figure 5-2. The proposed high level cost estimation solution is shown in Figure 5-3.

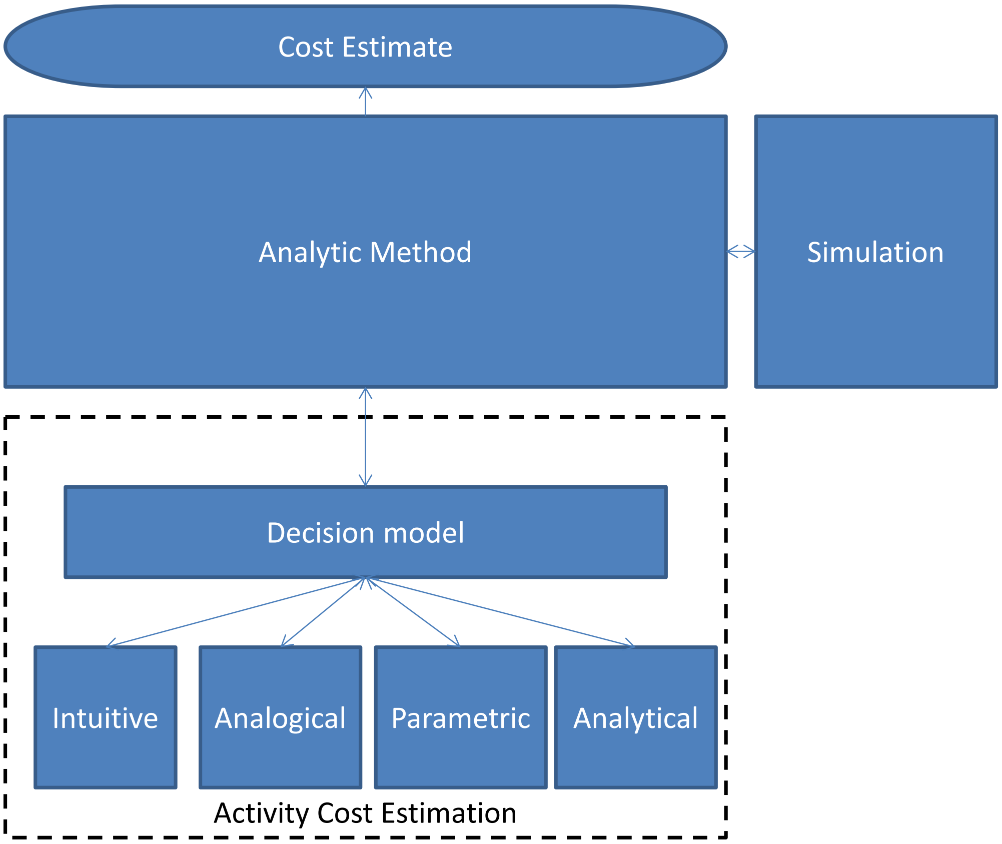


Figure 5-3 High level depiction of the proposed cost estimation solution for remanufacturing

5.5 Chapter 5 Summary

Within this chapter a detailed assessment of the cost estimation area in domains outside remanufacturing is conducted through a literature review. Key elements of a cost estimation are identified that can influence the method used. Cost estimation methods have then been identified and categorized into four areas; intuitive, analogical, parametric and analytical. A number of techniques to apply these cost estimation methods are then identified and described. Finally methods to enable uncertainty to be incorporated into the cost estimation have been assessed.

Based upon the knowledge gained from the broad review of cost estimation literature and the understanding of remanufacturing developed in Chapter 2, an analysis of suitable methods for the specific task of cost estimation for operational level remanufacturing was conducted. An analytical approach was deemed most appropriate for cost estimation within this scenario due to the estimate being conducted at an operational stage which enables a relatively detailed process of activities to be outlined. Due to the high level of uncertainty potentially present within the product description, it was decided that employing a simulation technique such as probability density function would resolve this issue. Finally a method is required to estimate individual activity costs. Due to the broad spectrum of knowledge bases found in remanufacturing it was decided that the cost estimation solution should provide methods for multiple approaches of individual activity costs estimation.

6 Design of the Cost Estimation Tool

The aim of this chapter is to present a detailed design for the cost estimation tool, identifying the particular algorithms required for cost and risk estimation and information requirements for case descriptions and knowledge base.

6.1 Chapter 6 Introduction

This chapter focuses upon outlining, in detail, a method of estimating cost and risk for product remanufacture. Within the previous chapter an understanding of cost estimation was developed and an outline of the key elements introduced. The structure of this chapter is formed around the outline of a cost estimate, shown in Figure 6-1. The cost estimation method is described in section 6.2 with outlines of the algorithms used to calculate costs and economic risk. The results output is also described within section 6.2.3. The information requirements are described within section 6.3. This includes the product and process models used to describe the remanufacture case, as well as the knowledge base in which cost information is stored.

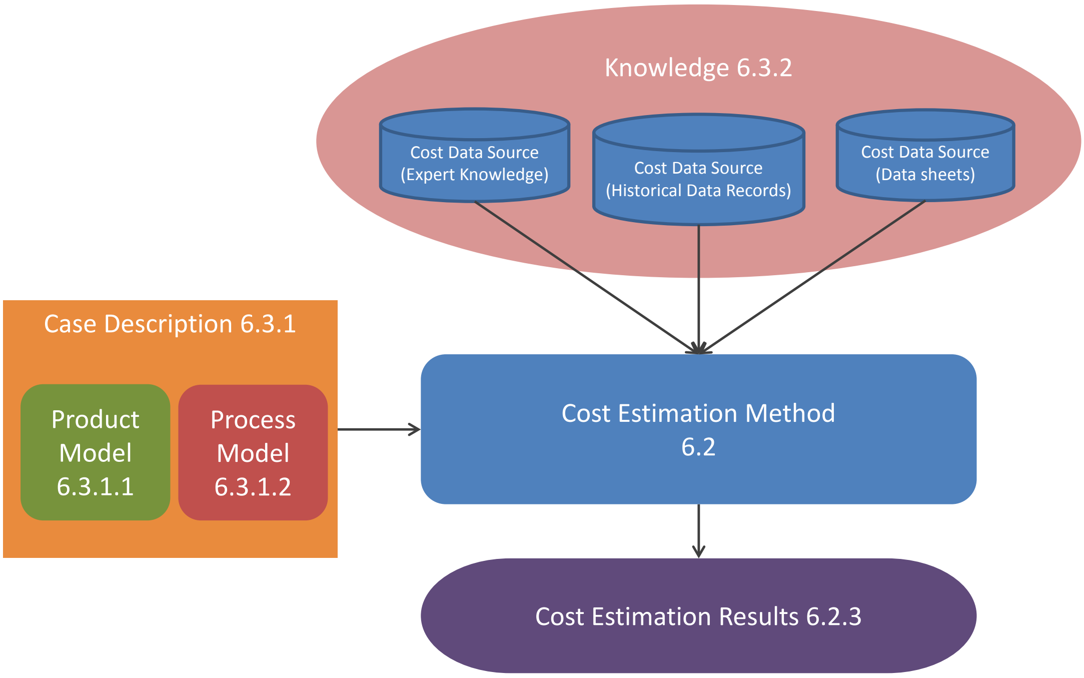


Figure 6-1 Overview of the cost estimation tool

6.2 Cost Estimation Method

As outlined within the previous chapter, an analytical method of calculating the cost is preferred. Due to the distinct activity phases required to conduct the remanufacturing process, highlighted within Chapter 2, analytical costing will be conducted upon an activity basis. However, due to the uncertainties regarding the exact number and type of activities that will be used within a particular remanufacturing process, a stochastic method is required. A Monte Carlo simulation technique has been adopted within this cost estimation method to assess the uncertainties. Stochastic methods are used to resolve uncertainties in determining particular activities whilst iterations of the entire cost estimation simulation are performed to determine overall results for cost and risk.

The overall cost estimation method algorithm can be divided into three key stages, as shown in Figure 6-2. Within the first stage (6.2.1) the cost of product remanufacture is calculated. The calculation uses a stochastic method to determine one particular instance of remanufacturing cost. The second stage (6.2.2) determines whether a convergence criterion has been achieved, if it has not then further iterations will take place by repeating the first stage (6.2.1), or if it has reached convergence, this will lead to the calculation of the results in the form of cost and risk metrics (6.2.3). From the array of iterations key metrics for cost and risk will be obtained which are to be used to assist decision making. Each of these stages, as shown in Figure 6-2, will now be discussed in greater depth.

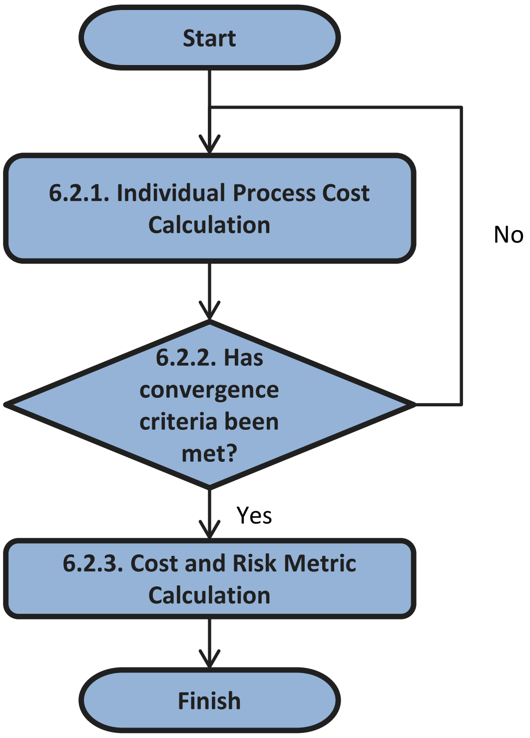


Figure 6-2 High level representation of the cost algorithm

6.2.1 Individual Process Cost Calculation

Due to the uncertain nature of remanufacturing it is impossible to predict an exact process cost. Instead this cost model is designed to identify a range of possible costs in order to provide information such as the minimum, maximum and mean cost values. This is done by predicting instances of remanufacturing using a stochastic cost model to resolve uncertainties. Repeating the cost model through multiple iterations will provide an array of potential remanufacturing process costs which can then be analysed to determine the cost metrics discussed in section 6.2.2. This current section explains in detail how the cost of a process instance is determined.

A high level depiction of the individual cost estimation process is presented in Figure 6-3. There are three elements to determine the cost of a possible instance of remanufacturing. The first element determines the workflow of activities required to complete remanufacture and is described in section 6.2.1.1. The second element calculates the cost of each activity and is described in section 6.2.1.2. Finally the third element sums the cost of each activity to produce a total cost of remanufacture and is described in section 6.2.1.3.

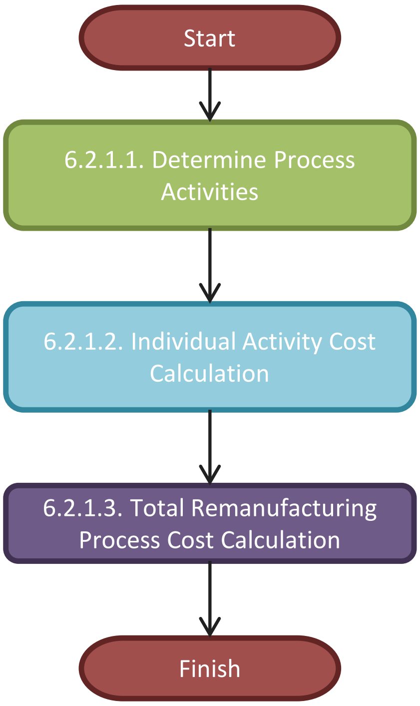


Figure 6-3 Key stages of the individual process cost calculation

6.2.1.1 Determination of Process Activities

In order to use the analytical costing approach a set of activities required to remanufacture a product must be determined. Although common remanufacturing stages will be required for every product undergoing remanufacture, such as disassembly, cleaning, rework, assembly and testing, the exact number and type of activities required will differ for each product. Reasons for this differing set of activities include the number and type of components within a product and their conditions. Additionally each business will conduct their own individual remanufacturing process which will be dictated by the requirements of the product and the capability of the business. This information regarding the product and process are to be contained within the models explained in detail within section 6.3.1. The algorithm outlined in this section must use the information contained within these models to generate a set of activities for which a cost of remanufacture can be calculated. This section will therefore specify the information requirements of the process and product models relative to activity determination and detail an algorithm for selecting the activities using the process and product models.

Process Information requirements for activity selection

- Remanufacturing activities
- Decisions
- Process Workflow

All of the potential activities which may occur during remanufacture are required to be contained within the process model. For each activity, the expected type of product or component should be recorded to enable the activity to be repeated if multiple components of a particular type are present. Information about decisions that occur during the remanufacturing process which influence activity selection are also required within the process model. These decisions can either represent findings from inspections that occur during remanufacture (such as should you reuse, remanufacture or replace component A), or other process logic that may occur, such as weight or size restrictions. Finally information related to the process workflow is required to link the decision logic with the appropriate remanufacturing activities. The workflow can be potentially complex when many decisions are required due to multiple components and potential remanufacturing activity options.

Product Information Requirements for activity selection

- Product Structure (Number and type of components)
- Component Information (linking to decision logic)

The structure of the product is required within the product model to identify the number and type of components contained within. A hierarchal structure is also required to ensure activities are not performed before disassembly has occurred. To dictate the decisions, product attributes are required. These are related to features such as the product condition, weight and size. These attribute requirements will vary between remanufacturing processes, so the product model must be robust to accommodate these variations.

Algorithm Design

The algorithm is designed to move through the process workflow, identifying the beginning of the workflow and move sequentially through, making decisions and recording activities encountered along the way, until it reaches the finish. This can allow a graphically designed process workflow to be used as part of the process model, enabling the user to visualise the paths that can be taken during remanufacture, making the creation of the process model more intuitive. In order to identify a suitable set of remanufacturing activities and comply with the specification in Chapter 4, the following requirements are necessary.

- Activities should be repeated if multiple components of the same type are present. This should be an automated function within the algorithm.
- Activities can only be conducted on a component if it has been exposed through disassembly. This is required to ensure that activities are not unnecessarily repeated by components which may be of the correct type but still remain in an assembly yet to be exposed.
- Activities should only be conducted once per component to avoid duplications.

The algorithm, shown in Figure 6-4, details how workflow through the process model is conducted. At this level only the process model is used. The process model is built using generic objects called process blocks. These process blocks enable the remanufacturing process to be described in detail, outlining the remanufacturing activities, the decisions, flow directions and start and finish points. Seven key process block types are used within the process model and are described in Table 6-1.

Table 6-1 The types of process block required to describe the process workflow

Process Block Type	**Function**
Start	Identify where the process begins
Finish	Identify where the process ends
Activity	Identify a cost incurring activity
Exclusive Gateway	A decision point where only one outcome occurs
Parallel Gateway	A point where the workflow splits into multiple parallel paths
Sequence Flow	A connecting object which describes how the process moves from one object to another
Sub Process	A container used to hold more detailed layer of the process which can be repeated if required.

Each of these process blocks invokes particular actions upon them being encountered. Start and Finish process blocks identify where the process begins and terminates respectively. The Sub Process block acts as a container to hold a more detailed layer of a process, which can allow process steps to be repeated for components. Activities signify specific cost incurring events that take place. Exclusive gateways represent decisions points where multiple routes are possible but only one is chosen. Parallel gateways allow for multiple paths to be followed in parallel with each other, such as component rework after disassembly. This has been added to allow more intuitive construction of the process workflow for the user.

In order to execute these process block functions, additional logic encapsulated within algorithms is required. Within Figure 6-4 five further algorithms have been identified;

- Component selection algorithm
- Exclusive split algorithm
- Parallel split algorithm
- Parallel join algorithm
- Sub Process algorithm

Each of the algorithms is explained in detail within the following sections.

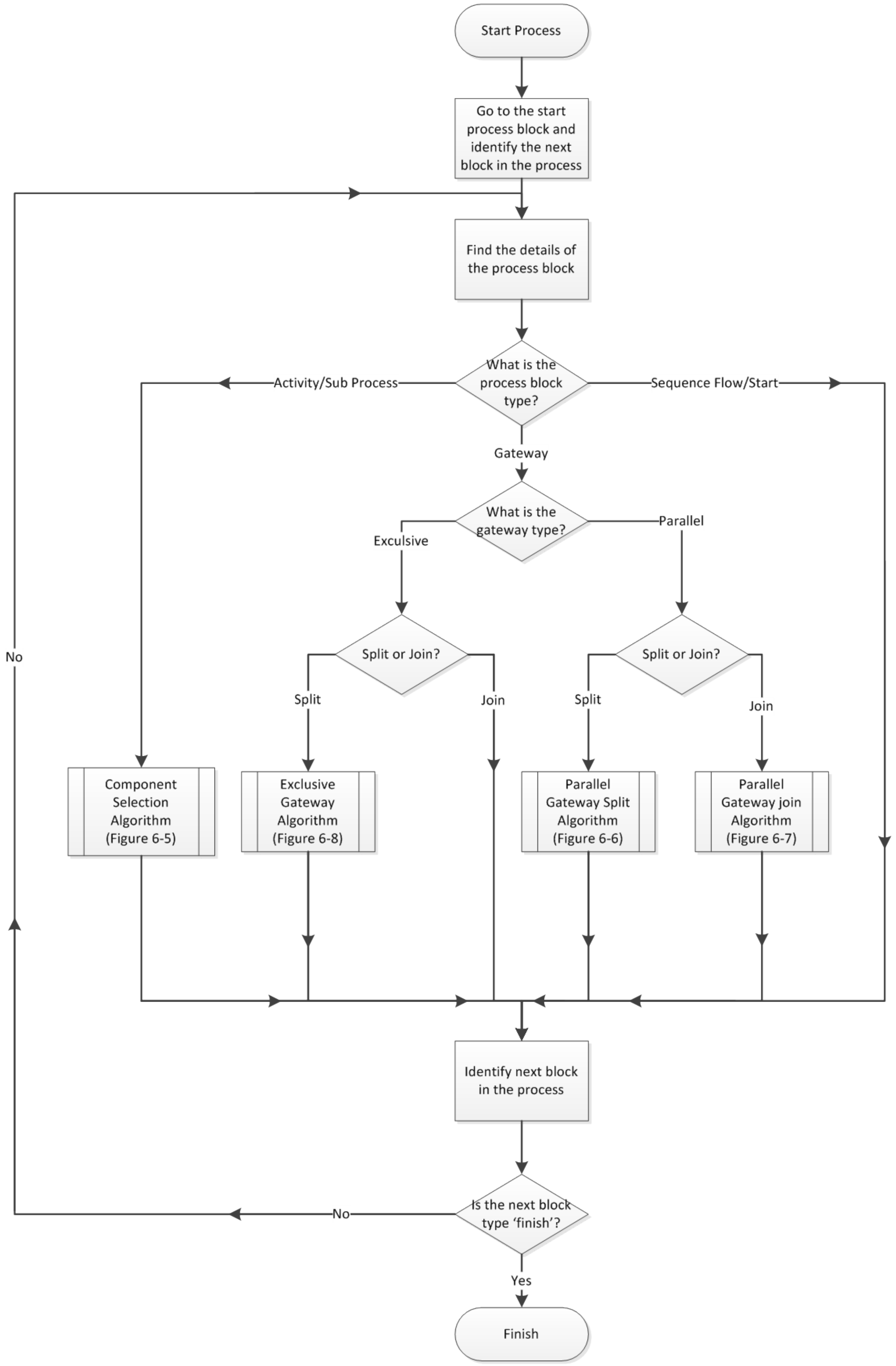


Figure 6-4 Algorithm to move through the remanufacturing process

6.2.1.1.1 Component Selection Algorithm

Once the component selection algorithm has been selected by the process workflow algorithm (Figure 6-4), either a remanufacturing activity is to be performed or a sub process will begin. However, to ensure that activities are repeated if multiple components are present and to keep track of the level at which components have been exposed through disassembly, an additional algorithm is required. This component selection algorithm enables this functionality through the monitoring of components within the system. Three storage locations are introduced to keep track of components within the cost estimate, bullet pointed below;

- Used Store
- Activity Queue
- Remanufactured Store

The Used Store contains the product and components waiting to be remanufactured. The Remanufactured Store contains products and components which have been remanufactured and are waiting to be assembled. The Activity Queue is used to hold products and components which are waiting to undergo an activity or sub process.

Although a common activity process block is defined in Table 6-1, there are in fact several different types of remanufacturing activity which influence how the products and components move through the storage locations. As identified within Chapter 2, the main activity types which make up the remanufacturing process are:

- Disassembly
- Assembly
- Inspection
- Cleaning
- Rework
- Testing

The exact movement of components between storage locations will vary depending upon the specific type of activity being conducted. For example disassembly will split a product or subassembly into its constituent components, whilst assembly will have the exact opposite effect. The movement of components between these storage locations is therefore facilitated through the algorithm detailed within Figure 6-5.

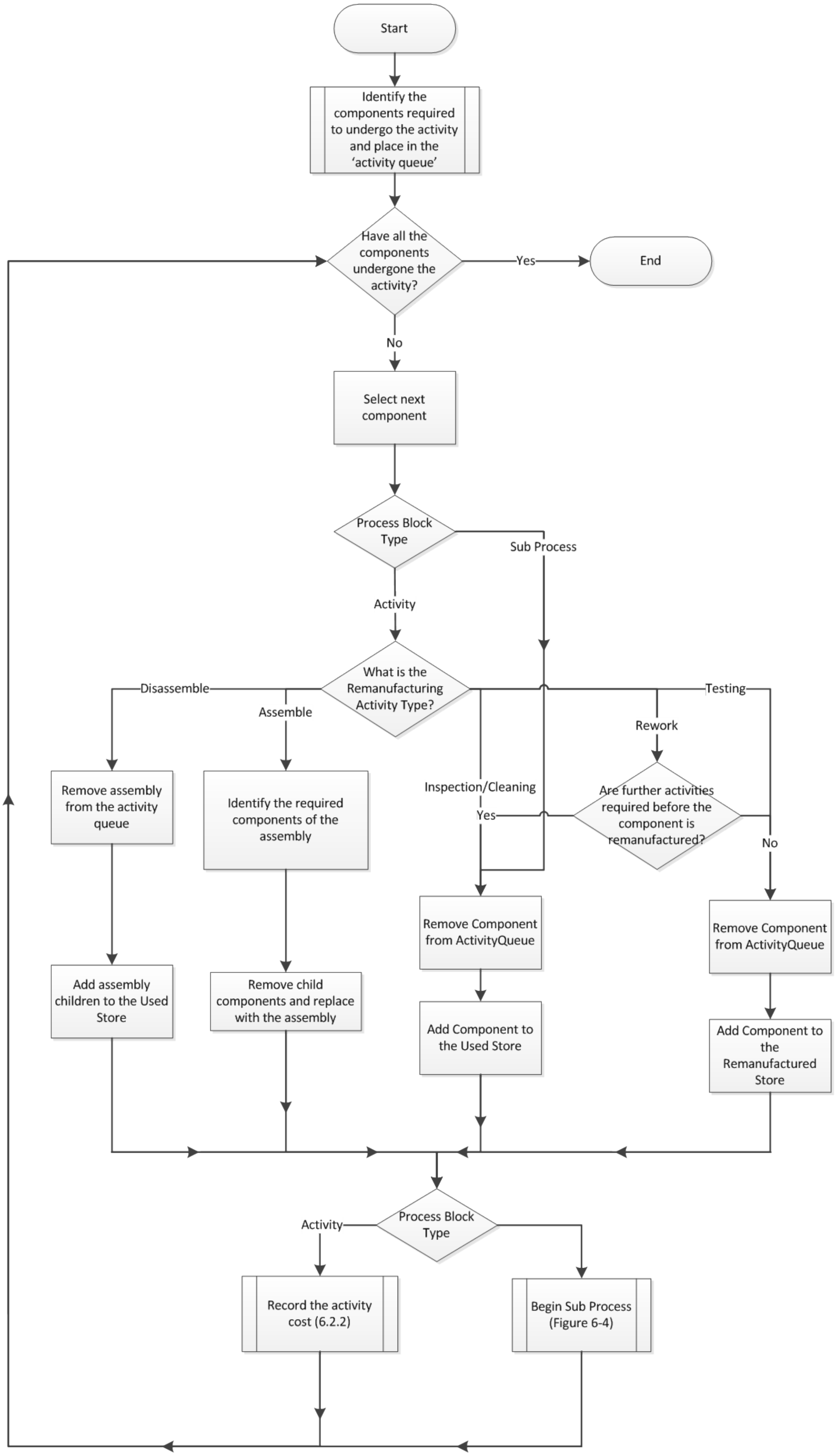


Figure 6-5 Flow diagram depicting the component selection algorithm

6.2.1.1.2 Parallel Gateway Algorithms

The parallel gateway is used to signify when activities can be conducted in parallel with each other. This usually occurs after disassembly when different component types are exposed. Although this action has little impact with the overall costing algorithm as it is not time dependant, it is useful to include this functionality as it can be easier to design process models which reflect what happens in reality and this also enables future upgradeability to time estimation models. Whilst the flow is depicted as parallel the prototype calculating algorithm currently works in a linear manner, thus the parallel work flow should be treated as pseudo for implementation purposes.

The split gateway is used to divide the flow into multiple paths and is shown in Figure 6-6. At the join gateway a decision must be made as to if all paths have been completed, as shown in Figure 6-7. If all paths have been completed then the flow will continue toward the finish, if not then the workflow will return to the original join gateway and follow an untaken pathway.

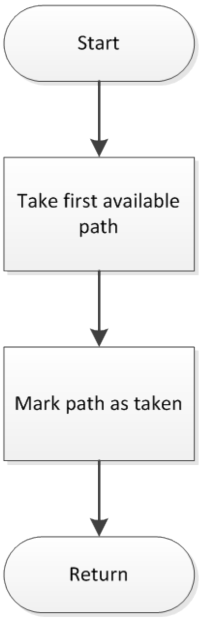


Figure 6-6 Parallel gateway split algorithm

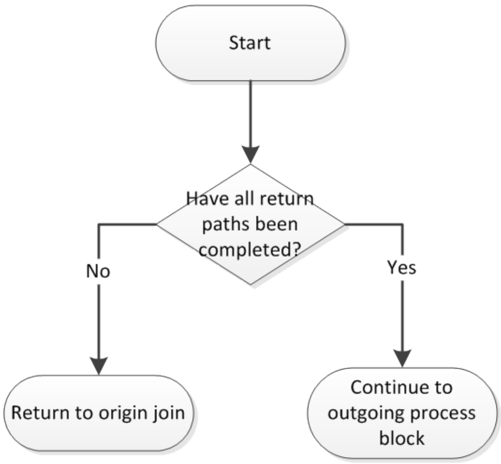


Figure 6-7 Parallel gateway join algorithm

6.2.1.1.3 Exclusive Gateway Algorithm

The exclusive gateway algorithm is required to determine which path the process should follow after passing through the exclusive gateway. The algorithm makes use of fuzzy sets to describe the probabilities of each pathway occurring and Monte Carlo analysis to select a particular path. The full algorithm is detailed in Figure 6-8.

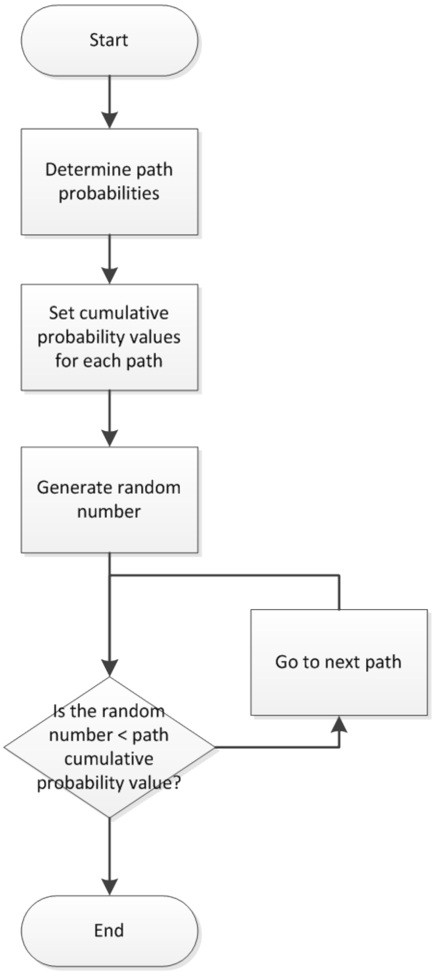


Figure 6-8 Exclusive gateway split algorithm including Monte Carlo analysis

The first step is to determine the probability of each pathway occurring. As the exclusive gateway usually coincides with an inspection activity, the decision is often attributed with product condition information. This relationship can be described using fuzzy sets. Fuzzy sets have been used due to the epistemic uncertainty found between the product condition and the chosen pathway. The product condition can be described in many ways, such as through direct sensor reading, a calculation based upon multiple sensors or qualitative description. However, until a detailed inspection is conducted there will always be uncertainty regarding the exact remanufacturing process required due to a lack of knowledge. Using intuitive or analogical knowledge, a fuzzy membership function can be derived to relate a condition metric and the possible pathways, as shown in Figure 6-9.

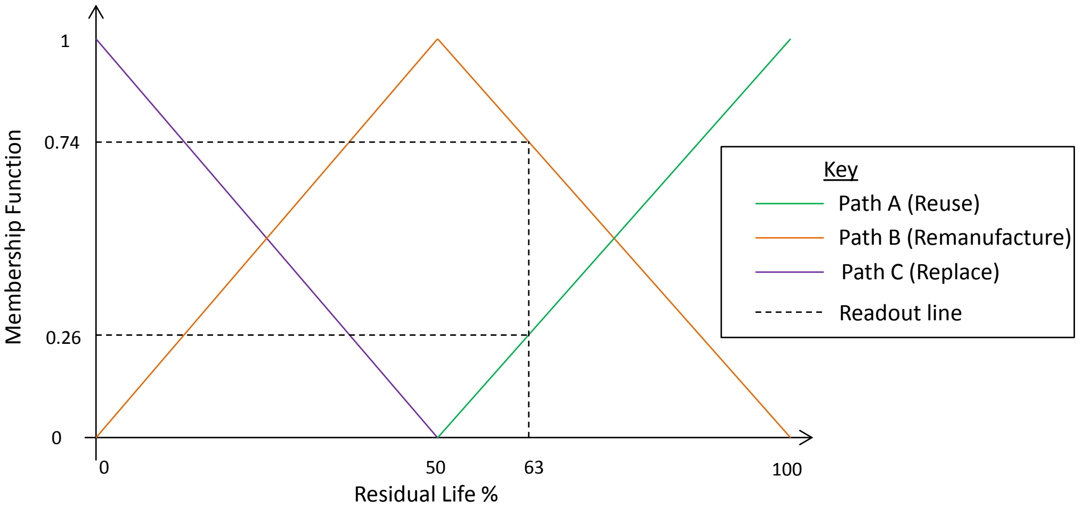


Figure 6-9 An example of a fuzzy membership function linking a component attribute such as reusability value to the probability of an output path occurring, values for 63% shown

Based upon these fuzzy sets, the probability of each path can be determined for a particular condition by reading the membership function value. For the example shown in Figure 6-9, using a reusability value (condition) of 63%, probabilities for each of the pathways shown in Figure 6-10 have been identified in Table 6-2.

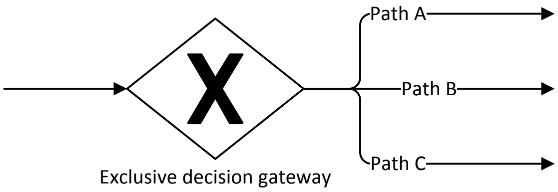


Figure 6-10 An example of an exclusive gateway

Table 6-2 Probabilities of the exclusive gateway shown in Figure 6-10

Gateway Outgoing Paths	Probability	Cumulative Probability
Path A	0.26	0.26
Path B	0.74	1
Path C	0	1

Monte Carlo analysis is used to determine which of the pathways is chosen for this particular calculation instance. To make use of this analysis, the probabilities need to be converted to cumulative probabilities as shown in Equation 1.

$$CProb_d = Prob_d + CProb_{d-1} \qquad 1$$

Where *CProb* is the cumulative probability value for a particular path n, *Prob* is the probability of a particular pathway d. Using these cumulative probability values, a random number is generated using an even probability distribution, and is compared to each cumulative probability in turn. If the random number is less than the cumulative probability for the path being considered, then that path is chosen, else the next path is considered, as shown in Figure 6-8.

6.2.1.1.4 Demonstrative Example

To demonstrate how the algorithms can be used with simple process and product models to generate a list of activities required for remanufacturing, an example is presented. The process model is represented within Figure 6-11 and the product model within Figure 6-12 and the information in Table 6-3.

Figure 6-11 illustrates a generic process model for a product containing components X and Y, such as the product example in Figure 6-12. The process begins with the disassembly of product A to reveal its constituent components (X, X and Y). A parallel gateway is then encountered in which components of type X follow one path whilst type Y follows the other. The path for component X leads to a sub process which has been expanded within the figure. The sub process begins with an inspection activity followed by an exclusive decision gateway. Components with minor damage follow the path to activity A whilst those with major damage follow the path to activity B. It should be noted that if this damage level is known prior to remanufacturing taking place i.e. during the cost estimation, then the cost estimation becomes deterministic in nature as there are no uncertainties. However in many situations this is not applicable as either the information is unknown, or at best fuzzy in nature. In this situation a stochastic approach is used to resolve the uncertainties in the decision. Once the decision is made the component continues along the work flow of its chosen path until it reaches the end point of the sub process. The entire sub process is then repeated again for the second X component. Meanwhile component Y follows its remanufacturing path in parallel with the X components. As only one component Y exists within the product activity C is only conducted once. Once all the components have reached the connecting parallel gateway, assembly A can be conducted to finish the remanufacturing process. The resulting activities can be seen in Table 6-3 assuming one X component was deemed to have minor damage and one with major damage.

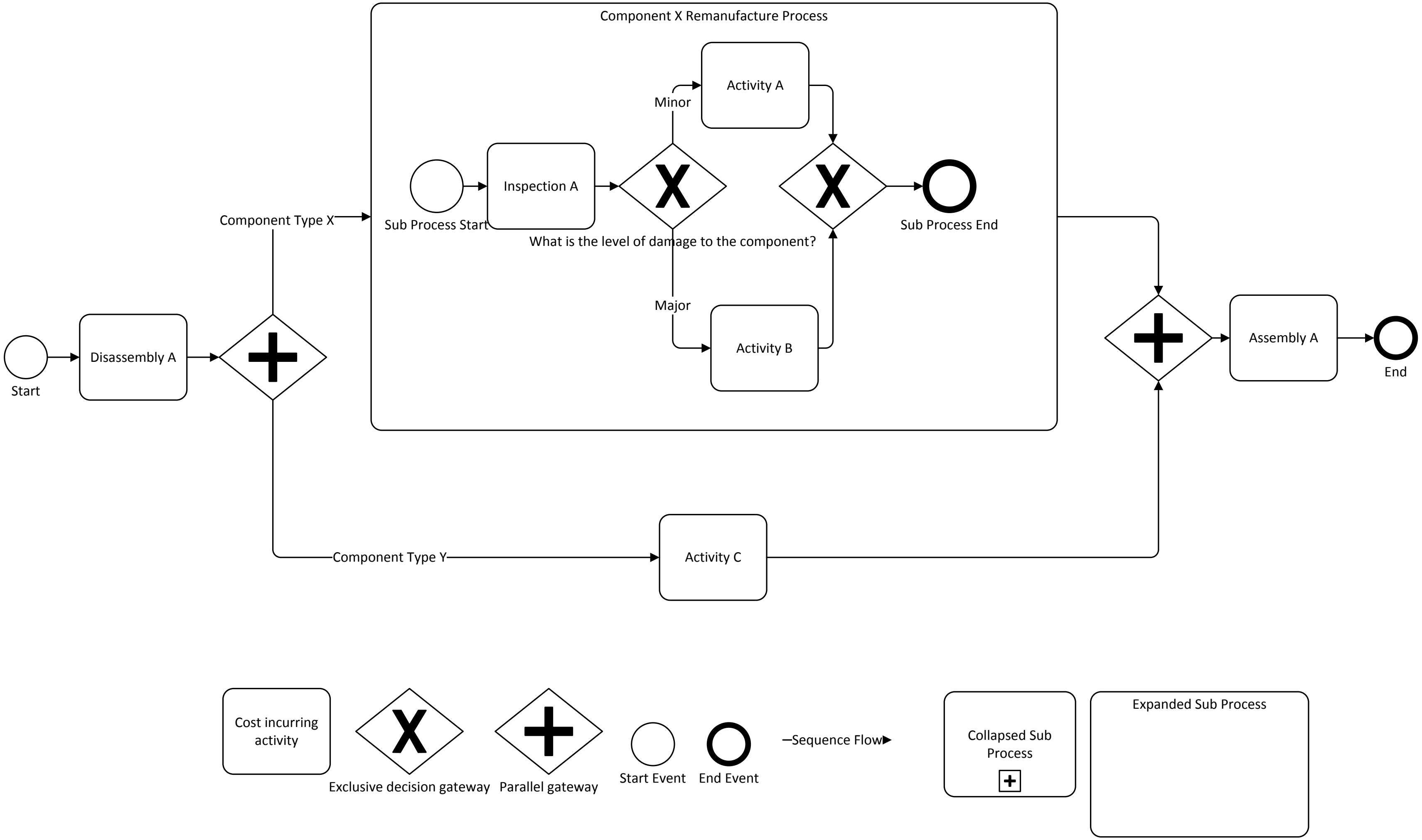


Figure 6-11 An example of a process model workflow described using Business Process Modelling Notation (BPMN) with additional key elements outlined

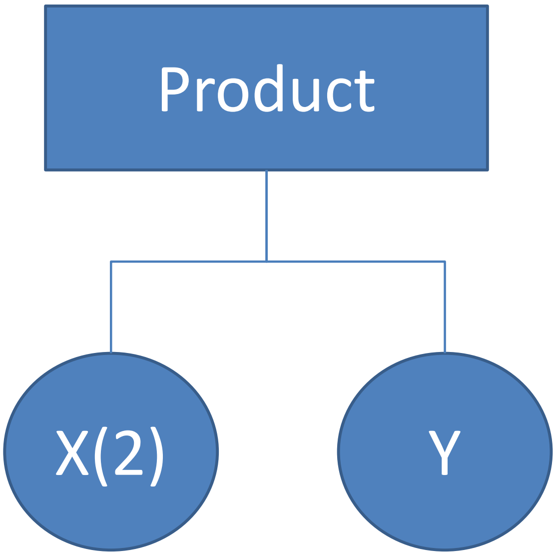


Figure 6-12 An example of the product model

Table 6-3 Product and component information and remanufacturing activity requirements determined from the process model

Product/Component Name	Damage Level	Activities incurred
Product	N/A	Disassembly A, Assembly A
Component X	Minor	Inspection A, Activity A
Component X	Major	Inspection A, Activity B
Component Y	N/A	Activity C

Again using the example above the effect of the component selection algorithm (6.2.1.1.1) can be demonstrated, illustrating the use of the three storage locations. The product to be remanufactured begins as the solitary item in the used product store (Table 6-4). When the process flow reaches an activity in which the product type is required (for this example Disassembly A in Figure 6-11), the product is moved from the used store to the activity queue (Table 6-5). As disassembly exposes the next level of the product, the product itself is removed and replaced with its components X, X and Y. These are placed back in the used store as they have yet to undergo remanufacture (Table 6-6).

Table 6-4 The product storage areas prior to the activity disassembly being selected

Used Store	Activity Queue	Remanufactured Store
Product		

Table 6-5 The product storage areas when the activity disassembly is selected

Used Store	Activity Queue	Remanufactured Store
	Product	

Table 6-6 The product storage areas after the activity disassembly has been conducted

Used Store	Activity Queue	Remanufactured Store
Component X, Component X, Component Y		

6.2.1.2 Individual Activity Cost Calculation

Once it is determined that an activity will be used as part of the overall remanufacturing process, a cost estimate is required. The cost of each activity can be calculated by the sum of the resource costs consumed by an activity as seen in Equation 2.

$$a(i) = \sum_{N_R}^{j} R_j \qquad 2$$

Where *a* is the activity cost for activity *i, R* is the cost of resource *j*, which forms a set of resources *J* for the activity *i*. The cost of each resource can be calculated by multiplying the quantity of each resource used by a cost per unit value, shown in Equation 3.

$$R = R_Q \times R_{C/U} \qquad 3$$

Where R_Q is the quantity of the resource used and $R_{C/U}$ is the unit cost of the resource. Therefore to determine the cost of conducting activity *i*, a set of resources, their quantities and their unit cost must be estimated.

There are several techniques which can be used to generate this set of resources as highlighted within section 5.3.2. The preferred technique for activity cost calculation will depend on the circumstances of the remanufacturer. Several remanufacturers will have experience of performing an activity for a particular part or product with little variation in resources used. In this circumstance an expert opinion of the resources required can be used within the calculation. However, in many circumstances this assumption is not valid as either the remanufacturer does not have enough experience or information to predict the resource requirements of performing the specific activity for the particular product. Here an alternative method is required for cost estimation where uncertainties exist. For this reason it was decided that a multi costing method be available within the costing tool. Two techniques are included within this proposed costing model, shown in Figure 6-13. The first technique uses a set of resources directly stored within a database which relates an activity with a specific product. The second method uses an analogical technique Case Based Reasoning (CBR) to identify similarities between past case knowledge and the new target case, explained in greater depth in section 5.3.2.2.1.

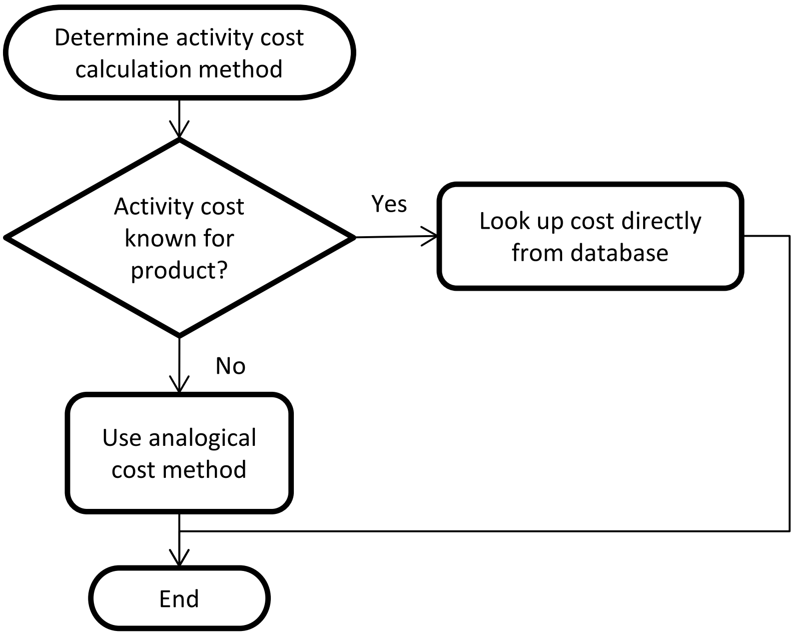


Figure 6-13 Flow diagram depicting the method of determining which activity cost method to use

6.2.1.2.1 Direct Look up

The first method of predicting activity resources is to simply query a database which contains information relating the resources required to conduct a particular activity for a particular product or component. For this information to exist, a good understanding of the resource requirements of the activity which will allow the prediction to be made with reasonable certainty is required. This information can be captured through interviews with experts, or through the analysis of historical datasets. This technique is useful therefore, in applications when relationships can be easily extracted due to deep understanding of the problem or when statistical records are large enough to extract stable relationships, such as high volume remanufacturing. However, this approach is not applicable when uncertainty exists.

Within the database a relationship between the product design and the estimated EoL activity cost is required. However, because this approach requires a good understanding of the activity with the particular product or component, it should not be used when MoL events (which will cause variation in the condition of the returned product) can affect the resources required by the remanufacturing activities.

6.2.1.2.2 Case Based Reasoning (CBR)

The alternative method used when uncertainties exist is based upon the analogical CBR technique. This method uses analogy to find similarities within past experience to predict what will happen in the new target case. This is the most appropriate costing method for activities which contain higher levels of uncertainty, such as the disassembly of complex products. The algorithm used to estimate a cost for this method is shown in Figure 6-14.

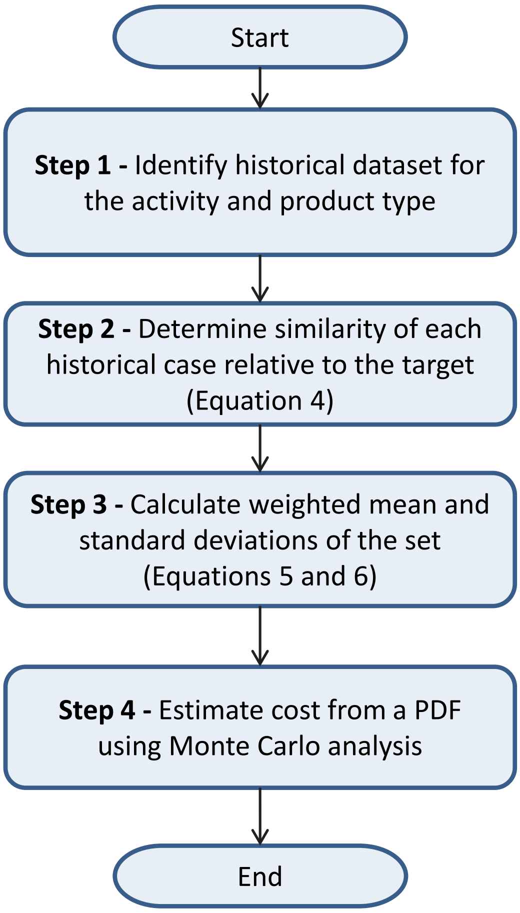


Figure 6-14 The analogical cost estimation algorithm

The first step requires a dataset to be identified, such as historical job records, where details about the product and the activity costs have been recorded. The similarity of the new target case is then measured against each of the historical cases of past activities. The method used to obtain the similarity score is shown in Equation 4.

$$Sim(T,l) = \frac{\sum_{m\in M} f(T,l_m)W_m}{\sum_{m\in M} W_m} \tag{4}$$

Where $Sim(T, l)$ is the similarity score between target case T and historical case l, $f(T, l_m)$is the individual attribute similarity between target case T and historical case S for attribute k, W_m is the weighted value of attributed m in the set of M.

Users are required to select product attributes to base the similarity score upon and apply weighting factors to the attributes. Individual weightings are scored between 0 and 1, with 0 indicating no importance and 1 indicating high importance. The selection and weighting of attributes requires understanding of factors which may affect the cost of performing these activities. Examples of key attributes include the manufacturer, model and power rating of a product or component.

A single method of calculating individual attribute similarity would be unsuitable due to the range of data types and values possible. For example assessing the similarity of texted attributes, such as a manufacturers name or model code requires a different method than comparing the similarity of numerical values, such as power. For this work two simple methods of calculating attribute similarity are proposed, although scope is available to add further methods within future work.

The first method allows string values to be compared, and simply determines if the two values are the same. If a match exists $f(T_k, S_k)$is set to 1, else it is set to 0.

The second method compares numerical values and assigns a weighting if the values are within ±10% of the target case. An exact match scores a value of 1, whilst all other values are based upon a linear equation which results in a 0 value at ± 10% of the target. All other values outside of the ±10% are also assigned 0.

The similarity calculation in Equation 4 is then applied to every case within the database. Each similarity score is then used as a weighting value to derive a statistical distribution from the database. The mean value is calculated using Equation 5 whilst the variance is calculated using Equation 6.

$$\mu_w = \frac{\sum_{l \in L} Sim(T, l) a(l)}{\sum_{l \in L} Sim(T, l)} \qquad 5$$

Where μ_w is the weighted mean cost of activity *i*.

$$\sigma_w^2 = \frac{\sum_{l \in L} Sim(T, l)(a(l) - \mu_w)^2}{\sum_{l \in L} Sim(T, l)} \qquad 6$$

Where σ_w^2 is the weighted variance of the mean cost of activity *i.*

Using these statistical properties, a distribution can be created to describe the cost of activity *i*. By describing the cost as a probability density function (PDF) the uncertainty within the estimate can be described. By weighting the historical data set using case based reasoning, similar cases can influence the cost estimate more significantly. A normal distribution was chosen as a suitable PDF. Monte Carlo analysis is then used to determine a particular cost value based upon the PDF to be used within the cost estimate.

6.2.1.3 Total Remanufacturing Cost

Once all the activities and costs have been determined for the entire remanufacturing process, the total remanufacturing cost is calculated by the summation of the activity costs, as shown in Equation 7.

$$C_{Reman} = \sum_{i \in I} a_i \tag{7}$$

6.2.2 Has Convergence Criteria Been Met

After a simulation iteration of the remanufacturing cost has been conducted, a convergence criteria is assessed to determine if further iterations are required. Boussabaine and Kirkham (2004) highlight the standard error of the mean statistic as a method of determining if suitable convergence has been met, shown in Equation 8.

$$\varepsilon = \frac{\alpha}{\sqrt{n}} \tag{8}$$

Where ε is the standard error of mean, α is the standard deviation of the variable of interest and n is the number of iterations conducted. By specifying the criteria of convergence for ε prior to cost estimation, for example as 1%, the actual value of ε can then be calculated after each iteration to determine whether further iterations are required.

6.2.3 Iteration and cost metric calculation

Within section 6.2.1 the total cost for one possible instance of remanufacture is calculated. However, this information alone is of little use to the decision maker as it does not explain the probability of that cost occurring or where it fits into the overall cost distribution. Therefore iterations of this cost calculation are conducted in order to build up a picture of the possible costs and also the economic risk of remanufacturing. Once a set of total costs have been calculated, simple statistical analysis of the results are performed to derive metrics such as the mean cost, shown in Equation 9.

$$\mu_{cost} = \frac{\sum_{n}^{i} C_{Reman\ i}}{n} \tag{9}$$

Additionally these costs can be displayed graphically within histograms and cumulative frequency distributions, as shown in Figure 6-15 and Figure 6-16 respectively.

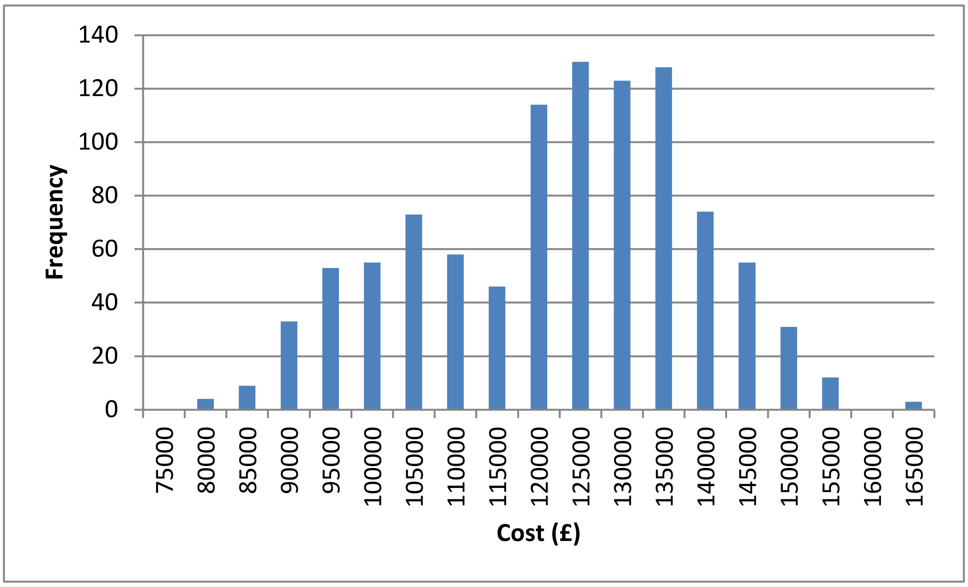


Figure 6-15 Histogram displaying frequency of costs calculation iterations estimates

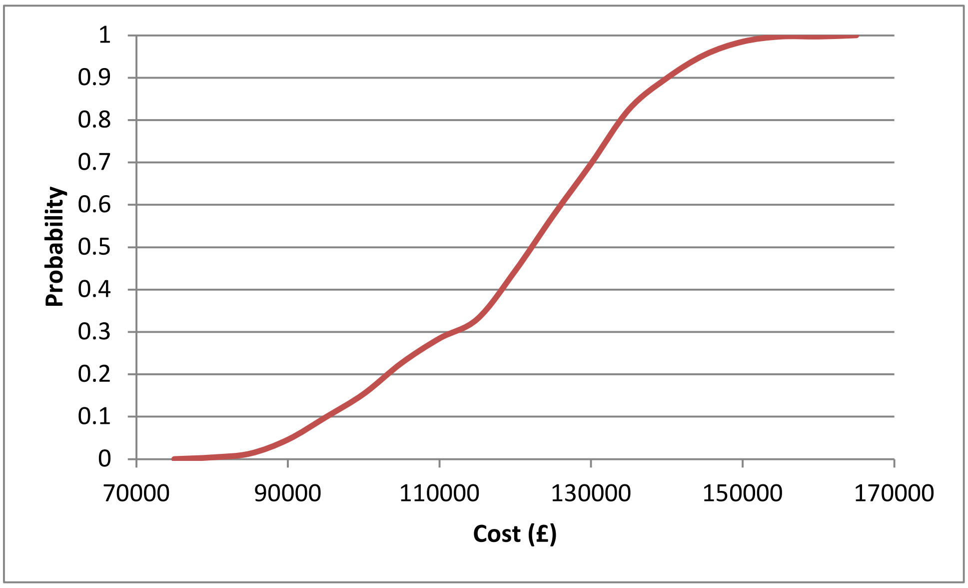


Figure 6-16 Cumulative probability curve based upon the results shown in the histogram in Figure 6-15

Risk metrics can be determined from the results of the simulation. Percentile values of the set are used to display the cost risk, shown in Table 6-7. These additional metrics are useful to inform the decision maker of the uncertainty and risk associated with the calculation.

Table 6-7 Cost calculation results displayed from the percentile values

Description	**Value (£)**	**Probability actual cost that is less than the value**
10th Percentile	100400	0.1
Mean	124637	0.5
90th Percentile	144900	0.9

6.3 Information Requirements

To use the cost estimation method described in section 6.2 a number of information sources are required. As outlined earlier in section 5.3.1, information can be delivered to the cost model either through the case description, or through the knowledge base to supply specific information relating to the costs. Within this section the information requirements of each of these sources are described.

Based upon the information presented within the design of the cost estimation method in section 6.2 the following index sets, variables and parameters which are required to estimate the cost of remanufacture are shown in Table 6-8, Table 6-9 and Table 6-10 respectively.

Table 6-8 Index sets used within the cost estimation method

Symbol	Description	Location	Source
$i \in I$	Where I ={1,…,N_a} activities used to remanufacture	Case Description	Process and Product Model
$j \in J$	Where J ={1,…,N_J} resources used in an activity	Knowledge Base	Activity Data
$k \in K$	Where K ={1,…,N_K} historical cost dataset	Knowledge Base	Product Model
$l \in L$	Where L ={1,…,N_L} similar cases	Knowledge Base	Product Model
$m \in M$	Where M ={1,…,N_M} Case Based Reasoning attributes for activity *i*	Case Description	Process Model
$d \in D$	Where D ={1,…,N_D} Outgoing pathways in an exclusive gateway	Case Description	Process Model
$e \in E$	Where I ={1,…,N_E} calculated remanufacture total cost instances	Calculation	N/A

Table 6-9 Costs used within the cost estimation method

Symbol	Description	Location	Source
C_{Reman}	Total cost to remanufacture a product	Calculation	Equation (7)
A_i	Cost of activity *i*	Calculation	Equation (2)
R_j	Cost of resource *j*	Calculation	Equation (3)
$R_{C/U}$	The cost rate of the resource *j*	Knowledge Base	Activity Data
$C_{Activity}$	Recorded cost of similar case product *i*	Knowledge Base	Product Model
μ_w	The weighted mean cost of activity *i*	Calculation	Equation (5)
μ_{Cost}	Mean total cost of remanufacturing iterations	Calculation	Equation (9)

Table 6-10 Parameters used within the cost estimation method

Symbol	Description	Location	Source
$Prob_d$	Probability of pathway *d* be chosen	Case Description	Process Model
$CProb_d$	Cumulative probability path *d* will be chosen	Calculation	Equation (1)
R_Q	Resource quantity	Knowledge Base	Activity Data
S	Source case k	Knowledge Base	Remanufacturer's Database
T	Target case	Case Description	Product Model
Sim_{Tk}	Similarity score between target case T and historical case k	Calculation	Equation (4)
W_i	Attribute weighting factor of activity *i*	Case Description	Process Model
ε	Standard Error Mean	Calculation	Equation (8)
σ_w^2	weighted variance of the mean cost of activity *i.*	Calculation	Equation (6)

Whilst several of these parameters are calculated within the cost estimation method, many are either directly stored, or indirectly derived from information within the product and process models, as highlighted in the tables.

6.3.1 Case Description

As discussed in section 5.3.1.2, the case description is required to describe the scenario which is being estimated. This description is represented using an information model. For the case of product remanufacture, two information models are required, the product and the process. This section outlines the specific requirements of the information models for the cost calculation, whilst a detailed implementation of them can be found in the Section 7.4.5.

6.3.1.1 Product Model

A model is required to represent information about the product being remanufactured to the cost estimation method. Users will enter information related to the product into this model which will then be used by the cost estimation method during calculation. The key requirements of the product model are to represent information related to the components and their structure within the product and also important attribute information that may affect activities and decisions within the remanufacturing process. As stated within the overall software tool requirements (Chapter 4), this information should be represented within a generic structure which can accommodate the specific requirements of different product and component types. Based upon these requirements, the product model has been divided into three key areas;

- Product Structure
- Design Attributes
- Life Cycle Information

Each area is now discussed in greater depth to identify their specific requirements.

The product structure is an important part of the product model as it affects the number and type activities that can be required by the remanufacturing process, discussed within section 6.2.1.1. The product structure is required to identify the subassemblies and components that make up the overall product, and their physical connections with each other for the purpose of assembly and disassembly. An example of a simple product structure hierarchy can be seen in Figure 6-17 and this includes information of the component name and its physical relationship with components and subassemblies within the overall product.

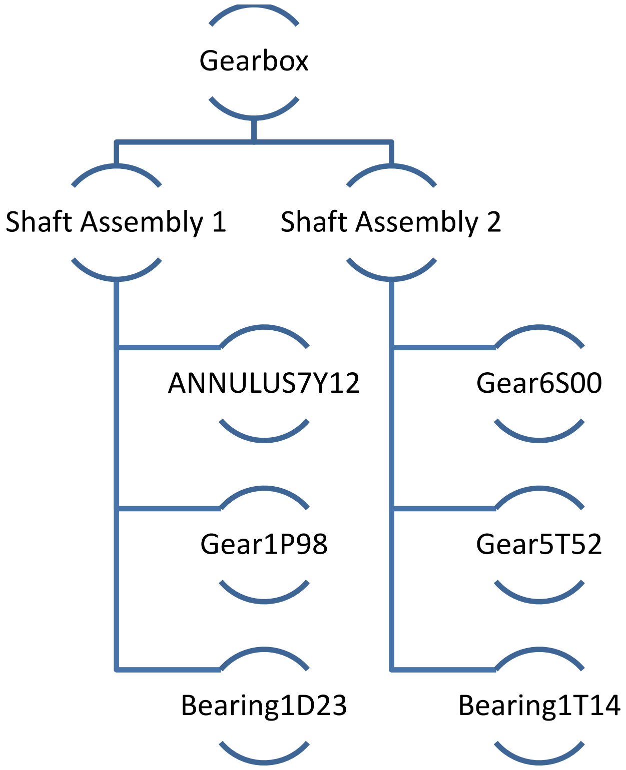


Figure 6-17 Hierarchal representation of the product structure

The next area of information required within the product model focuses upon design attributes. This encapsulates information related to the product design, performance specifications and identification information, including manufacturer and model. Several of these attributes will be common to most products and components, and include identifying information such as the manufacturer, model, and unique id number. However, many of the attributes will be specific to particular products and components. These attributes describe specific features of a product, for example engine information may include attributes such as the power output, number of cylinders and fuel type. A generic method is required to describe these specific attributes within the product model. This information is required by the cost estimation method to enable searching for cost information or assessing the similarities between the target and historical cases.

Finally life cycle information is required by the product model to describe specific events, activities and measurements that may have occurred to a specific product or component over its life. Lifecycle information has been described within three stages, discussed within Chapter 2, which are: Beginning of Life (BoL), Middle of Life (MoL) and End of Life (EoL). BoL data relates back to its manufacturing history such as where and when it was manufactured. MoL information relates to the use phase of a product’s life and can include information related to service and maintenance reports as well as sensor data recorded on the product. This data can be used in the cost estimation method in a similar manner to the design specification information in that it is useful to search for similarities between target and historical cases within the case based reasoning algorithm. EoL data includes information related to the product’s EoL, such as remanufacturing processes, activities and their costs. Capturing EoL information is important since this can be compared with similar historic cases to predict costs for the target case. EoL information is not required within the product model for the case description as it is assumed the product being considered for remanufacture has no EoL information.

Existing product models were then investigated to identify current methods of describing this type of information. Product models of interest included the QLM product model (The Open Group QLM Work Group:2012) and the product recovery data model described by Um et al. (2008).

Based upon the specific requirements outlined above, a high level design for the product data model is proposed within Table 6-11. The exact implementation of the product model can be found in section 7.4.4. The model consists of seven object types, each being used to record particular information related to the product.

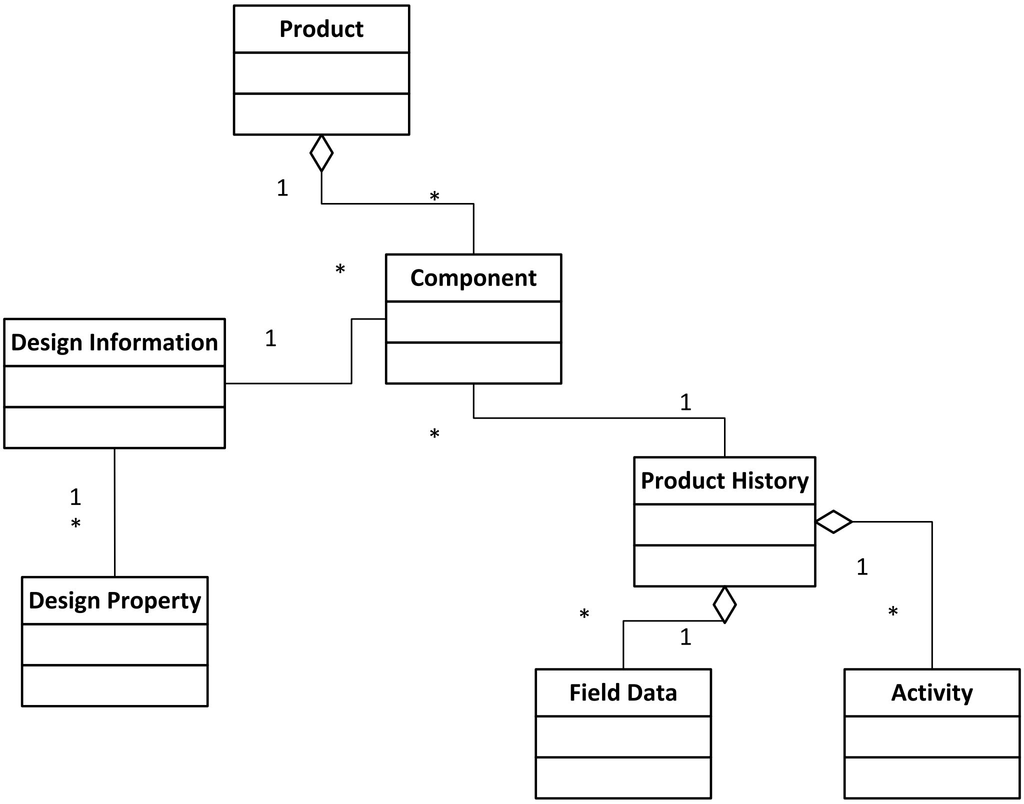


Figure 6-18 UML Object representation of the product model structure

Table 6-11 Product model objects

Object	Description
Product	Represents the overall product. It contains component objects which represent the actual components within the product.
Component	Describes information about individual components and subassemblies within the product, including structural relationships between components. Also contains Design Information and Product History objects.
Design Information	Contains information related to the design attributes. It describes information specifically related to common identification methods as well as the component type. It also contains Design Property objects.
Product History	Is used to store information related to the life cycle of a product. Each object of this type is used for a particular part of the life cycle phase and contains Activity and Field Data objects to record specific information.
Design Property	Describes specific product or component attributes in a generic manner. The key information stored in this object includes meta information about the attribute, such as a description and unit of measurement, as well as the particular value.
Activity	Describes particular activities conducted upon the product or component during the life cycle. This can include scheduled maintenance activities and owner changes. Key information recorded in this class includes the type of activity performed and the resources used.
Field Data	Describes information recorded from a measurement during the product life cycle. This can range from measurements such as sensor readings to visual inspection reports. Key information to be recorded within this object is the type of measurement, the unit of measurement, the value of the measurement and the date of the measurement.

6.3.1.2 Process Model

The process model is used to describe information regarding specifically how the product is remanufactured. Within section 6.2.1.1.1, it was identified that requirements for estimating the number and type of activities included information about the possible activities that may be incurred, the decisions required within the process and the workflow linking the decisions with the activities. Based upon these requirements a set of objects were proposed to represent the remanufacturing process. Additionally, the activity costing methods require additional information to be contained within the process model, such as the product attributes which may affect the activity cost used within the case based reasoning algorithm detailed in section 6.2.1.2.2.

Existing methods of expressing process models were analysed for their applicability to the process model requirements, including Business Process Model Notation (BPMN) (Object Management Group Business Process Model and Notation:2014) and IDEF3 (Knowledge Based Systems:2014).

Based upon the requirements outlined above and influences from existing process modelling methods, particularly BPMN, the following process model structure has been proposed within Table 6-12. The full implementation can be found within section 7.4.5. The model consists of nine objects, each being used to store particular information about the process. Multiple instances of each object may be required to within the process model. A description of the information contained within each of the objects is found within Table 6-12. The objects falling under the category of process blocks are directly derived from BPMN and are used to describe the process workflow. A graphical representation of these objects can be seen in Figure 6-19, with an example of an entire workflow shown in Figure 6-20.

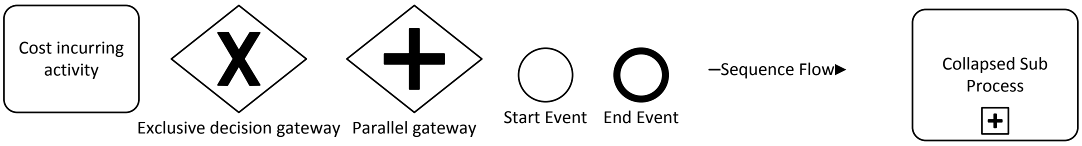


Figure 6-19 A key of the object types used by the BPMN graphical modelling system

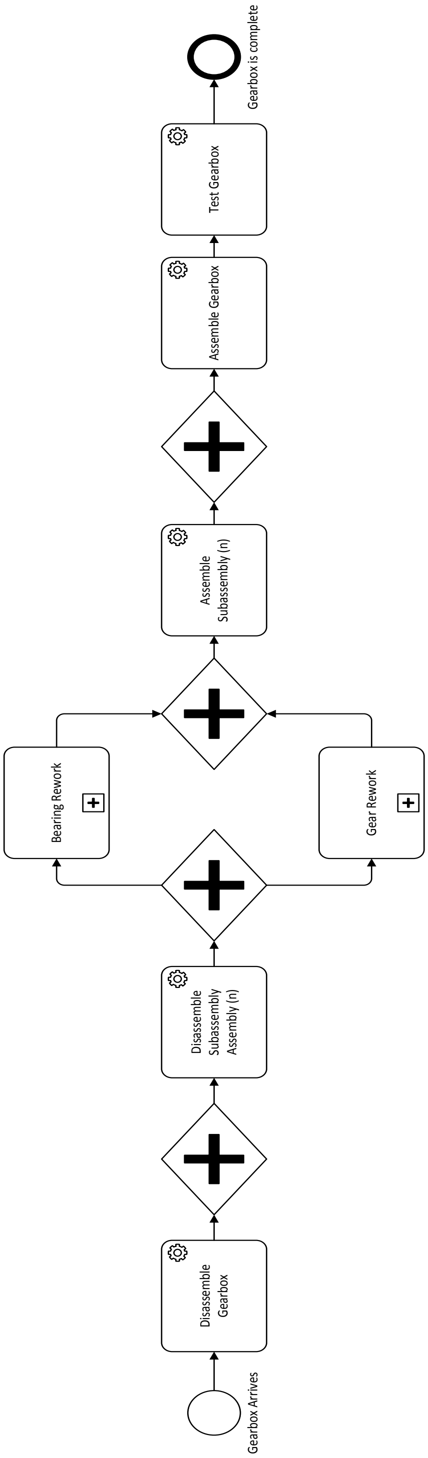


Figure 6-20 A graphical example of a BPMN process model

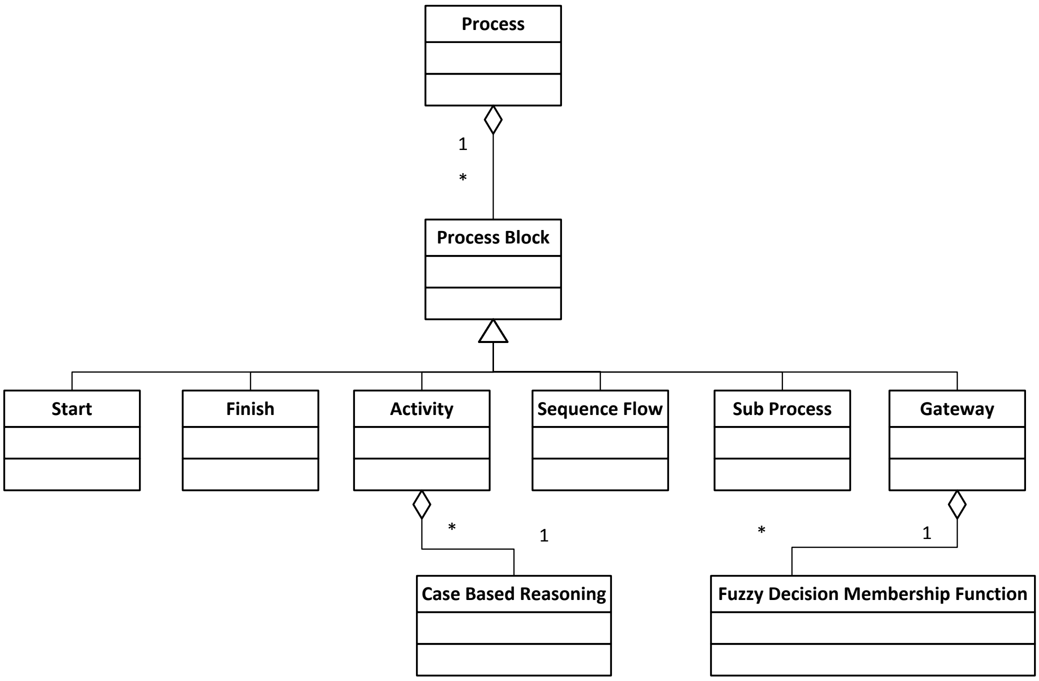


Figure 6-21 Object representation of the process model structure

Table 6-12 Process model objects

Object		**Description**
Process		Represents the overall remanufacturing process. Contained within the process object are a process blocks that make up the process work flow. Start and Finish points are stated and additionally the product type for which the process is remanufacturing.
Process Blocks	Start	Identifies the starting point of the process
	Finish	Identifies the finishing point of the process
	Activity	Identifies a cost incurring activity within the process workflow. Information about the activity is also contained within this object including the type of activity (such as disassembly, assembly, rework, inspection or testing), the product or component which the activity is to conducted upon, identification information including name and case based reasoning information, held within Case Based Reasoning objects.
	Gateway	Identifies when the process workflow can divide into, or converge from multiple paths. The information contained within this object includes the gateway type, either exclusive signifying a decision point or parallel signifying that the all routes are taken. If it is an exclusive gate then additional information regarding the decision logic is contained within Fuzzy Decision Membership Function objects.
	Sequence Flow	This object depicts how the process moves from one process block object to another. This is done by stating the object the flow moves from and the object it moves to.
	Sub Process	A container used to hold more detailed layer of the process. This holds information about the sub process workflow, represented as a Process object.
Case Based Reasoning		Describes information required to perform the case based reasoning calculation to assess the similarity between products or components for the activity. Each case based reasoning object contains information about only one component attribute, therefore multiple objects may be required to depict the full relationship. The key information required to be contained within this object includes the product attribute, the weighting, and the matching type, such as a numeric or semantic.
Fuzzy Decision Membership Function		This object contains information to describe the fuzzy logic membership function for one outgoing pathway from an exclusive gateway. Therefore multiple objects of this type will be required to describe the logic within an Exclusive Gateway. The specific information contained describes the shape of the fuzzy function including the minimum and maximum values.

6.3.2 Knowledge Base

The knowledge base is formed of information accessible to the cost estimation method on demand, which is used to assist the cost estimate regarding specific costs. The knowledge base is structured based upon different types of information sources, namely analogical and intuitive. The analogical knowledge base comprises of historical job records, which includes information about previously remanufactured products and their costs. The intuitive knowledge base lists the specific resource requirements of a particular activity for a particular product or component. This information can be collected through interviews with experts or through the analysis of recorded datasets. For the software tool being developed here the information is contained within databases.

6.3.2.1 Historical Job Records

Historical job records contain information regarding the activities and costs used to remanufacture products by a business in the past. Specifically the information recorded relates to the products or components which were remanufactured, the activities conducted, the resources used.

This information is stored within relational databases by the remanufacturing businesses, which are then accessed by the cost estimation method through queries to search for relevant information. To effectively query the database an information model is required to represent the data in a manner which is suitable for the cost estimation method. Mapping between the database tables and the information model will show where the information required by the cost estimation method is stored within the databases.

The information structure used to represent the historical job records is the same as the product model described in section 6.3.1.1. Product information can be stored within the product, component, design information and design property objects, whilst the activity information can be recorded within the product history and activity objects.

6.3.2.2 Activity Estimate Sets

Activity estimate sets contain information relating the costs between particular products and components, and remanufacturing activities. This information differs to the historical job records in the method in which they are obtained. Unlike the historical record set, which records costs of activity instances, the activity estimate sets are intuitive estimates obtained through periodic interviews with employees identifying the resource requirements of activities for particular products. This method of recording cost information is more suitable to businesses operating high volume remanufacturing upon a small product set, as it may be too costly to make records regarding every activity conducted and a high number of remanufacturing instances are required to generate confidence in the records.

As with the historical job records, the activity estimate sets will also require an information model to represent the data used within the cost estimation method. The product model in section 6.3.1.1

can be used to describe information about the product, however it cannot be used to represent information about the activity cost in the way the historical job records can. This is because this information is an estimate about a particular product design type, rather than a record of an actual activity. Therefore a new model is required to represent this information. The new model is proposed within Table 6-13 and contains four objects.

Table 6-13 Activity estimate data requirements

Object	Description
Product Design	Contains information about the product or component being remanufactured. Only meta information is required, such as design id, manufacturer and model for identification purposes.
Activity	Contains high level information to identify a particular activity, such as a name or id.
Activity Resource Requirements	Relates the product design and the activity information and estimates the resources required to complete the activity, specifically the resources id and the quantity
Resource	This contains all the information about a particular resource such as the name, type, unit of measurement and cost per unit.

6.4 Chapter 6 Summary

Within this chapter a method of cost estimation for remanufacturing is described. The method is designed to meet the requirements of remanufacturing cost estimation described in Chapter 4 and draws upon methods and techniques for cost estimation founded within other domains which were explored in Chapter 5.

An analytical approach has been used which aims to identify the individual cost consuming activities required to remanufacture a product. The model accounts for both aleatory and epistemic uncertainties encountered within the estimation process. Uncertainties within the remanufacturing work flow, caused by a combination of aleatory and epistemic factors, are resolved using a combination of fuzzy sets and stochastic Monte Carlo analysis, whilst epistemic uncertainty regarding the cost of conducting activities are determined using case based reasoning. The entire approach is then iterated to generate a range of total cost outcomes for product remanufacture which enables the cost risk to be assessed. Statistical analysis of these total costs is conducted to generate desired cost and risk metrics used by the decision maker.

The information requirements of the cost method have been discussed. Two major information sources exist, the case description and the knowledge base. The case description describes the remanufacturing scenario for which the cost calculation is being conducted, and is formed of a product and process model. The information contained within the knowledge base is required to store specific cost information that can be used within the estimate. Two knowledge bases are used by the cost estimation method, one to store analogical information in the form of historic job records, which are used by the case based reasoning element of cost estimation, and another to store intuitive estimates of the specific resource requirements related to a particular product and activity.

The novelty of this cost estimation tool lies within the ability to generate a cost for remanufacturing when uncertainties are present within the product. Within the next chapter the software implementation of the cost estimation tool is described.

7 Software Implementation of the Cost Estimation Tool

7.1 Chapter 7 Introduction

This chapter explains how the cost calculation method, described in the previous chapter, has been implemented within software. The implementation phase was conducted in conjunction with the PREMANUS project and thus some of the implementation decisions were influenced by this larger project. The software has been implemented in the style of service oriented architecture (SOA).

The chapter begins with a description of the PREMANUS project and how the cost calculation fits within the system SOA architecture. Next, the Object Oriented Programming (OOP) paradigm which has been used to structure the cost calculation tool is discussed along with the graphical notation used to describe the implementation throughout this chapter. The model implementation is then presented including the system architecture and detailed explanation of the static structure of the classes including their attributes, methods and relationships with one another.

7.2 PREMANUS Project Software Architecture

The software implementation of the cost tool has been conducted in collaboration with the PREMANUS European project (PREMANUS:2013a). The aim of the project is to provide remanufacturers with business decision support systems that can utilise information from scattered data sources and partners. The PREMANUS architecture can be seen in Figure 7-1. The contribution of this work is to provide one element of a larger Business Decision Support System (BDSS), i.e. BDSS1 shown in Figure 7-1. The software architecture of the implemented prototype cost tool has therefore been heavily influenced by the overall PREMANUS architecture which was designed as a Service Oriented Architecture (SOA).

SOA is defined by Microsoft (2013) as ‘a loosely-coupled architecture designed to meet the business needs of the organization’. Instead of traditional single technology applications designed to meet a specific business requirement, SOA utilises discrete reusable services which are independent of product or technology. These services can be considered as ‘black boxes’ to the consumers of the service, who are only required to know the data inputs and the expected data outputs (The Open Group:2013). As the individual services are interoperable, clients (consumers of the service) do not need to use the same technology as the service, therefore a service written in Java programming language can be accessed by a client written in the Python programming language. Data is exchanged via interoperable communication standards such as XML. This has advantages within large business systems that include improved scalability and reusability of service modules for multiple purposes (Erl:2008).

A web service is a specific method of realising a SOA using standard web protocols to send messages between services. Within the PREMANUS project the Representational State Transfer (REST) web services have been used which make use of the HTTP protocols GET, PUT, POST and Delete.

The cost calculation tool detailed in this thesis has been implemented as a web service and provides support to other BDSS functions by providing cost estimates for a particular product undergoing a certain remanufacturing process.

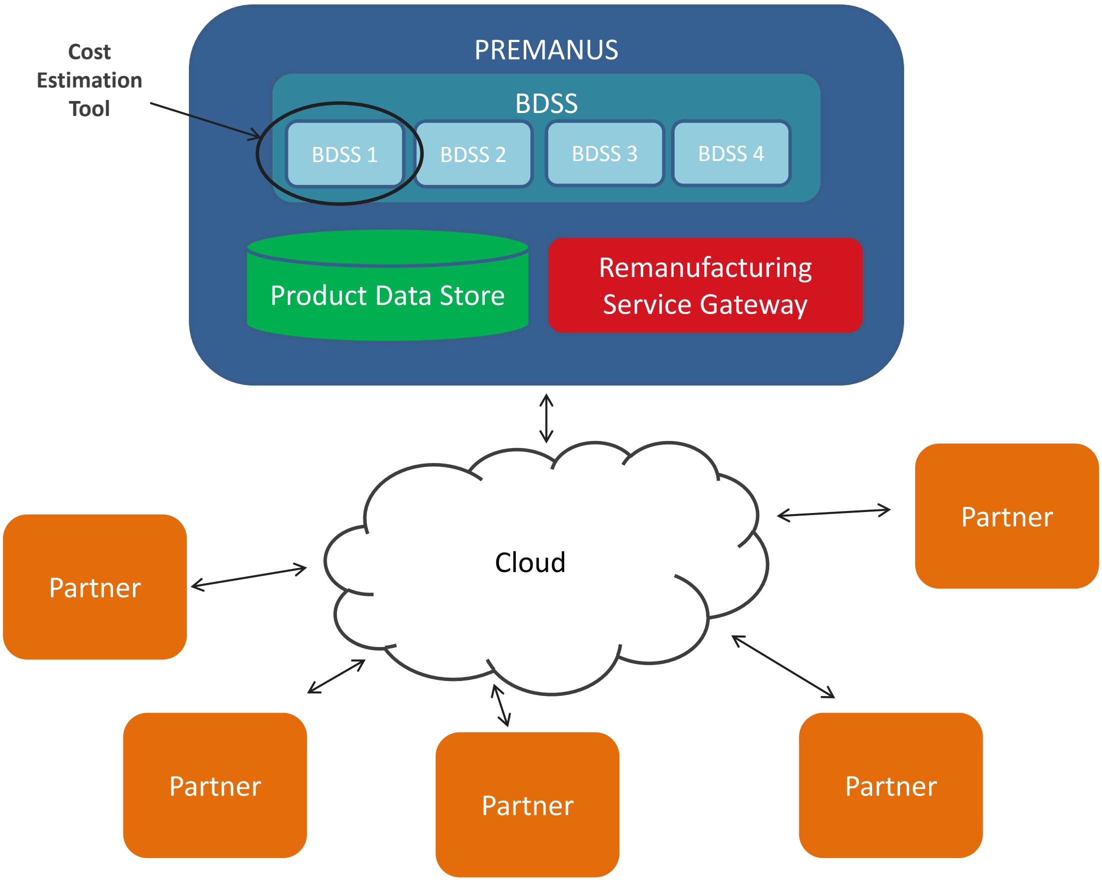


Figure 7-1 Overview of the PREMANUS system architecture

7.3 Object Oriented Principles of Software Implementation

The cost calculation tool itself has been programmed using the Object Oriented Programming (OOP) paradigm. OOP encapsulates both data and functions into discrete objects. This differs from other programming paradigms, such as procedural where data and functions have no distinct relationship to one another. By enabling this tight encapsulation of data within objects, code can be easily scaled and transferred between projects. The encapsulation of both data and functions can also allow objects to be described as abstractions of reality.

Table 7-1 lists a number of concepts used within OOP, along with definitions taken from a taxonomy of OOP by Armstrong (2006). These terms are used throughout this chapter to describe how the cost estimation tool has been programed.

Table 7-1 Object Oriented Programming conectps from Armstrong (2006) unless otherwise stated

Construct	Concept	Definition
Structure	Abstraction	Creating classes to simplify aspects of reality using distinctions inherent to the problem
	Aggregation	A special type of association where a client class contains one or more instances of another class (Riley, 2002)
	Association	a relationship that occurs anytime that one class is used within another (Riley, 2002)
	Attribute	An entity that names a single characteristic of an object's state (Riley:2002)
	Class	a description of the organisation and actions shared by one or more similar objects
	Encapsulation	a technique for designing classes and objects that restricts access to the data and behaviour by defining a limited set of messages that an object of that class can receive
	Inheritance	The data and behaviour of one class is included in or used as the basis for another class
	Object	an individual, identifiable item, either real or abstract, which contains data about itself and descriptions of its manipulations of the data
Behaviour	Message Passing	An object sends data to another object or asks another object to invoke a method
	Method	A way to access, set, or manipulate an object's information
	Polymorphism	Different classes may respond differently to the same message and each implement it appropriately
	Multiplicity	Multiplicity places a constraint upon an association by indicating the number of relationships that can occur between objects

Unified Modelling Language (UML) is a standardised modelling language which enables the visual representation of object oriented programming design and implementation. Many of the concepts described above are visualised using UML diagrams which allow the design and implementation to be shown. Within this thesis the UML class diagram is used to describe the static structure of the cost estimation tool implemented within the object oriented paradigm. Figure 7-2 highlights the graphical representations for some of concepts described in Table 7-1. Example notations of multiplicity are shown in Table 7-2.

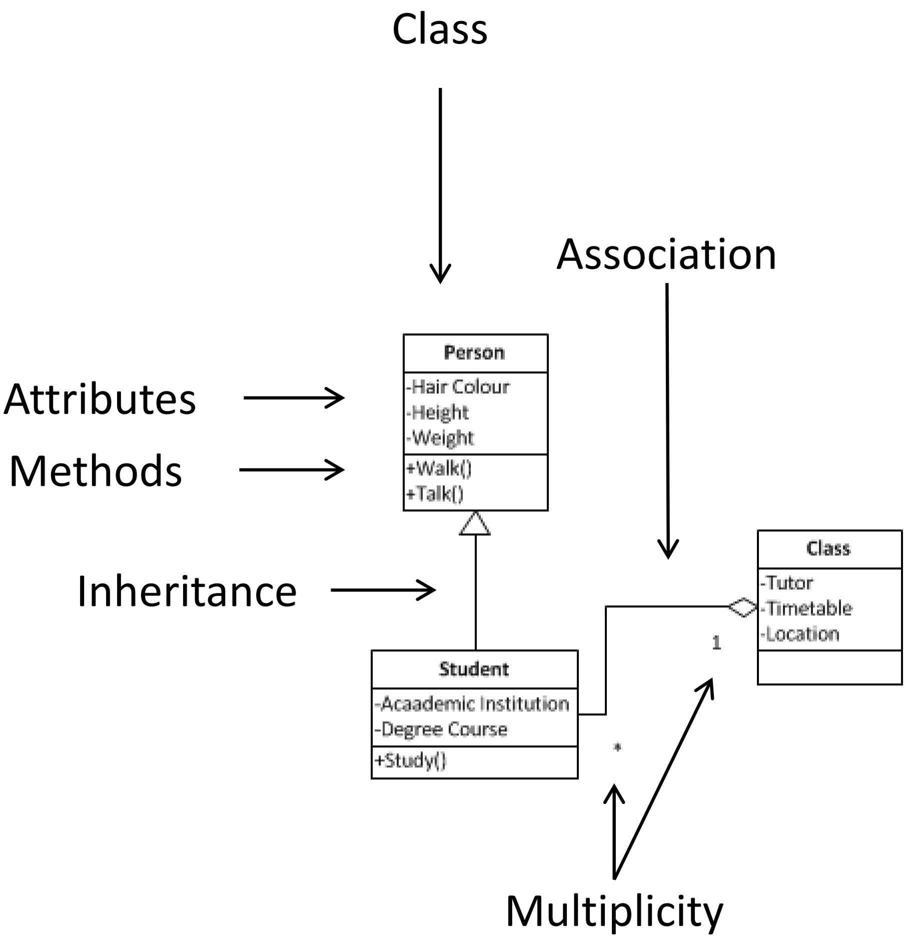


Figure 7-2 Class diagrams in UML

Table 7-2 Definition of the UML notations for multiplicity

Multiplicity	Number of elements
0..1	Zero or one instance
1	Exactly one instance
*	Multiple instances
1..*	At least 1 instance
5..5	Exactly 5 instances
m..n	At least m but no more than n instances

7.4 Model Implementation

7.4.1 Architecture of cost calculation

The overall architecture of the cost estimation tool is shown in Figure 7-3. The key elements of the architecture are the client (user interface) and the web service. The client acts as a user interface to allow the case descriptions to be formed (product and process models) and the results of the estimate to be displayed. The Web Service hosts the cost estimate tool and the knowledge base which comprises of a historic job record and activity estimate sets database.

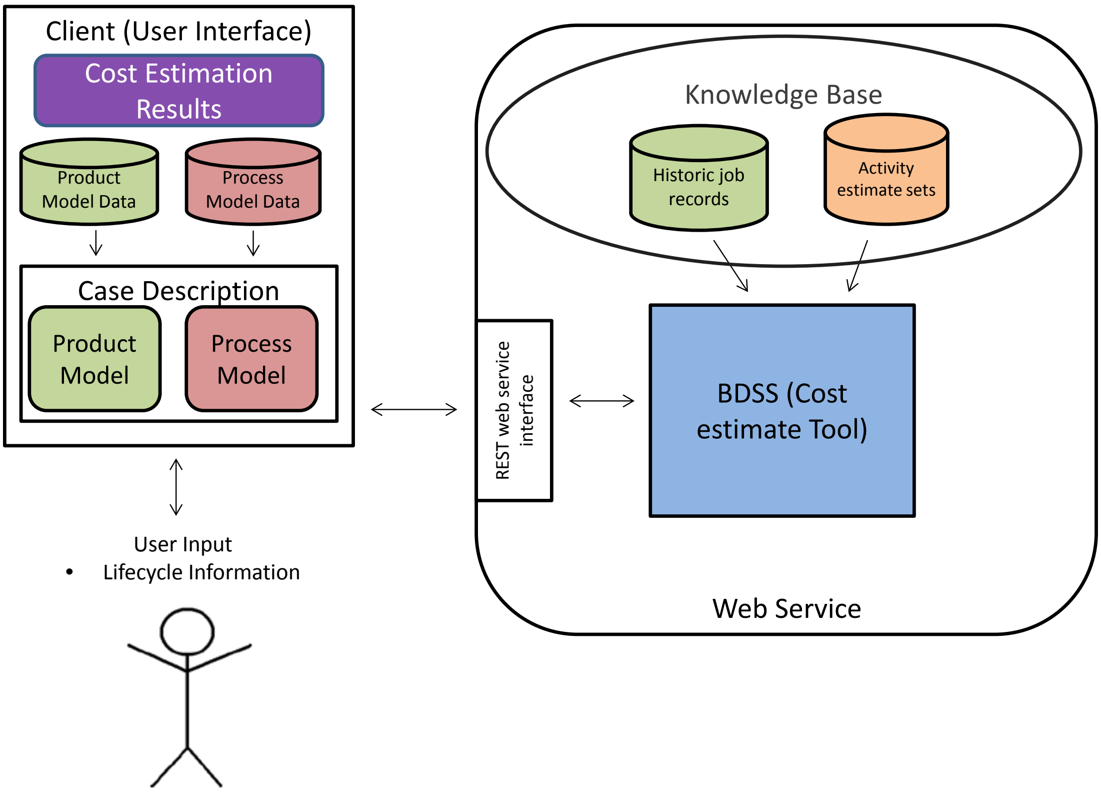


Figure 7-3 Architecture of the cost calculation implemented as a web service

The user interacts with the client and constructs a product and process model, for the cost estimate that is to be calculated, using information contained within the product and process model database. The constructed product and process models are then sent to the cost estimation tool, over the internet using REST web services. The cost tool calculates a result, using the information contained within the knowledge base databases when required. Results are then sent back to the client, using the REST web services. The software has been developed within the Microsoft .Net format, using the Visual Basic language. This supports OOP which was the chosen method of developing the software.

The implementation of the cost model is a key outcome of the research and this chapter explains how the designs of the previous chapter have been implemented within this system.

7.4.2 Cost Estimate Tool Structure

The structure of the cost estimation tool can be seen in Figure 7-3. It is formed of three main areas: the cost estimation model, the product model and the process model. Each of these areas are now discussed in greater depth.

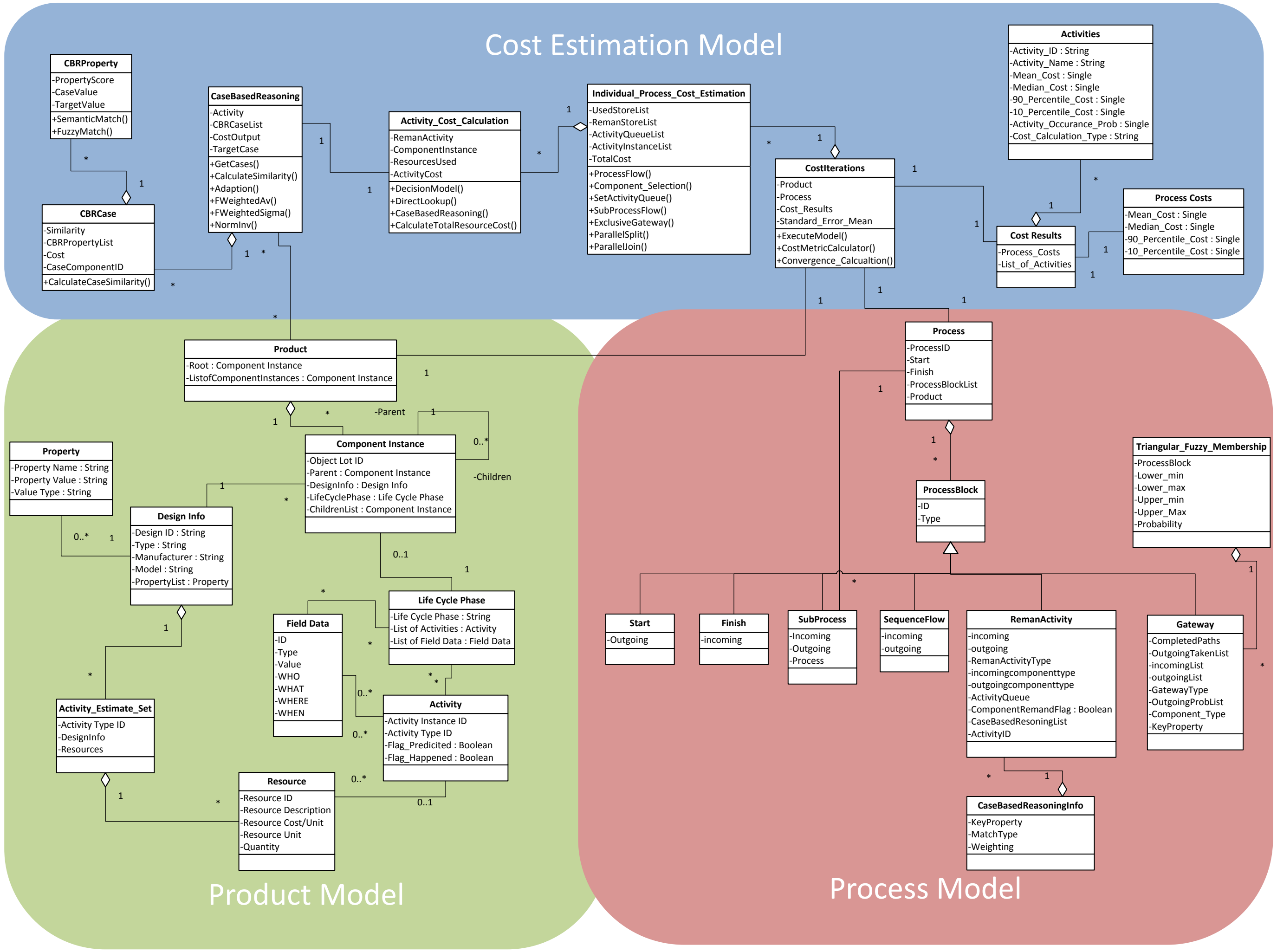


Figure 7-4 UML class diagram depicting the overall structure of the cost estimate tool

7.4.3 Cost Estimation Method

The cost estimation method is the implementation of the calculation algorithms designed within section 6.2. It is composed of nine key classes; CostIteration, StochasticProcessFlowEngine, ActivityCostEstimator, CaseBasedReasoning, CBRCase, CBRProperty, Cost_Results, Process_Costs and Activities, with their structure shown in Figure 7-5. Each class implements a particular part of the overall design. The details of each class are now described below.

CostIteration Class

This forms the basis of the cost estimation model and is the key class which the user interacts with to execute the entire cost calculation. It represents the implementation of the design in Figure 6-2. It is comprised of the following attributes and methods;

- *Product* - The product model which the cost is being estimated, using the product class.
- *Process* – The process model which the cost is being estimated, using the process class.
- *Cost_Results* – The calculated results of the cost estimate as an instance of the Cost_Results class.
- *Standard_Error_Mean* – The standard error mean value which the user wishes calculations be conducted to.
- *ExecuteModel()* method initiates the entire cost calculation described in section 6.2 .
- *CostMetricCalcualtor()* – Method which calculates the values of the cost results. Based upon the design in 6.2.3.
- *Convergence_Calculation()* – Method which calculates the actual standard error mean (equation 8) and compares the result to the attribute *Standard_Error_Mean* to determine if more iterations are required.

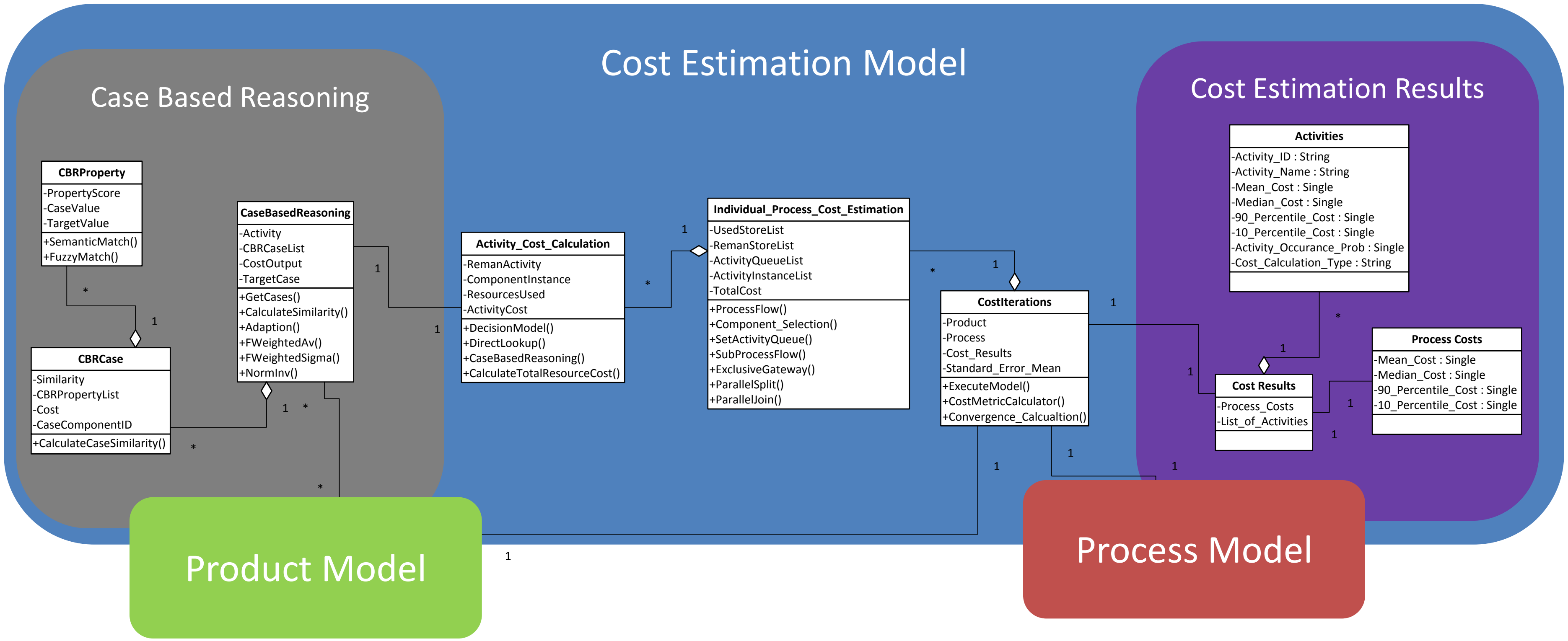


Figure 7-5 Class diagram of the cost estimation method structure

Individual_Process_Cost_Estimation Class

This class is used to estimate the cost of a single remanufacturing instance, described in section 6.2.1. Multiple instances of this class will be created during the estimation process, with each instance representing a cost calculation iteration. It is comprised of the following attributes and methods;

- *UsedStoreList* – A list of component instances which are yet to be remanufactured, described in section 6.2.1.1.1.
- *RemanStoreList* - A list of component instances which have been remanufactured section 6.2.1.1.1.
- *ActivityQueueList* - A list of component instances waiting to undergo a particular activity section 6.2.1.1.1.
- *ActivityInstanceCostList* – A list of *ActivityCostEstimstor* class instances which each represent a record of each activity occurrence.
- *ProcessFlow()* - Method refers to the algorithm described in Figure 6-4.
- *Component_Selection()* - Method refers to the algorithm described in Figure 6-5.
- *SetActivityQueue()*- Method refers to the algorithm described using tables Table 6-4, Table 6-5 and Table 6-6.
- *SubProcessFlow()*- Method refers to the algorithm described in Figure 6-4, but for sub process.
- *ExclusiveGateway()*- Method refers to the algorithm described in Figure 6-8.
- *ParallelSpilt()*- Method refers to the algorithm described in Figure 6-6.
- *ParallelJoin()*- Method refers to the algorithm described in Figure 6-7.

Activity_Cost_Calculation Class

This class represents the cost estimate for an individual activity, as described in section 6.2.1.2.

- *RemanActivity* - The activity which the cost is being calculated for, using an instance of the RemanActivity class from the process model.
- *ComponentInstance*- The component the activity is being calculated for, using an instance of the componentInstance class from the product model.
- *ResourcesUsed* - A list of estimated resources required by the activity.
- *Activity Cost* – The total cost of the activity.
- *DecisionModel()* – The method is used to estimate the resources and thus the cost of an activity. This uses the algorithm detailed in Figure 6-13 which chooses whether to use either direct activity cost data or cased base reasoning.
- *DirectLookup()* – Method looks up the required activity cost information from the activity cost database.

- *CaseBasedReasoning()* –Generates a new *CaseBasedReasoning* object.
- *CalculateTotalResourceCost()* –Sums the individual resource cost to generate a total activity cost.

The next group of classes constitute the cased based reasoning element of the cost estimation method.

CaseBasedReasoning Class

This class forms the main case based reasoning element and represents the overall case based reasoning enquiry for an activity instance.

- *Activity* – The activity which the case based reasoning is being conducted for.
- *CBRCaseList* – A list containing each of the similar cases.
- *CostOutput* – The calculated cost of the activity using the CBR method
- *TargetCase* - The product or component which the case based reasoning is being conducted for.
- *GetCases()* – Gets a set of cases in which the activity has been performed and is of the same component type.
- *CalculateSimilarity()*- Calculates the similarity of each case against the target
- *Adaption()* – Adapts the results of the most similar cases to generate the output cost estimate.
- *FWeightedAv()* – Calculates the weighted average cost of the cases using equation 5.
- *FWeightedSigma()* – Calculates the weighted standard deviation of the case costs using equation 6.
- *NormInv()* – Based upon a normal probability density function described using the results of *FWeightedAv()* and *FWeightedSigma(),* a cost is generated by using a random variable to represent a probability value, as described in section 6.2.1.2.2.

CBRCase Class

This class represents a single case that is being examined by the *CaseBasedReasoning* class.

- *Similarity* – Contains the result of the similarity calculation for each case.
- *CBRPropertyList* – A list of all the properties (CBRProperty) associated to the CBRCase.
- *Cost* – The cost value of the case
- *CaseComponentID* – The unique id for each case.
- *CalculateCaseSimilarity()*- Calculates the similarity for each case using Equation 4.

CBRProperty Class

This class represents a single property of the *CBRCase* class.

- *PropertyScore* - A value between 0 and 1 representing the similarity of a particular property.
- *CaseValue* - Contains the actual value of the case property.
- *TargetValue* - Holds the value of the target property.
- *SemanticMatch()* – A method which identifies whether the *CaseValue* and *TargetValue* are an exact match and produces a resulting value of either 0 or 1 (see section 6.2.1.2.2).
- *FuzzyMatch()* – A method is used for integer values and produces a continuous function based upon a triangular distribution about the *TargetValue* (see section 6.2.1.2.2).

The final group of classes used within the cost estimation method are used to represent the cost results.

Cost Results Class

This is the main class which forms the output of the cost calculation. It contains three attributes which are explained below.

- *Process_Costs* – The Process Cost attribute is of type Process Costs and contains the key cost information for the entire process.
- *List_of_Activities* – The List_of_Activities attribute contains a list of type Activities. It contains all the possible activities that may be incurred within the remanufacturing process.

Process_Costs Class

This class represents the key cost metrics for the overall remanufacturing process.

- *Mean_Cost* – Displays the mean cost for the whole process.
- *Median_Cost* – Displays the median cost for the whole process.
- *90_Percentile_Cost* – Displays the 90th cost percentile, indicating the upper risk.
- *10_Percentile_Cost* – Displays the 10th cost percentile, indicating the lower risk.

Activities Class

The activities class is used to store specific information related to the activities which the cost estimation model has deemed may occur.

- *Activity_ID* – Displays the ID of the activity
- *Activity_Name* – Displays the name of the activity
- *Mean_Cost* – The mean cost of the activity
- *Median _Cost* – The median cost of the activity
- *90_Percentile_Cost* – The 90th cost percentile of the activity, indicting upper risk
- *10_Percentile_Cost* – The 10th cost percentile of the activity, indicating lower risk

- *Activity_Occurnace_Prob* – States the probability that the activity will occur (between 0 and 1)
- *Cost_Calcualtion_Type* – Indicates the method used to calculate activity cost (either direct lookup or case based reasoning)

7.4.4 Product Model

The product model comprises of an information structure which allows the product to be described to include the information specified in section 6.3.1.1. It is also used to represent information obtained from the knowledge base within the cost estimation tool, namely the historic job records and the activity estimate sets. The product model used within the implemented software is shown in Figure 7-6. It contains four main areas; product structure, design specification and attributes, life information and activity estimate sets. The first three areas were identified in section 6.3.1.1 in references to the description of the product model, whilst the activity estimate set is required from section 6.3.2.2 . The structure of the model is influenced by the QLM data model (The Open Group QLM Work Group:2012) and the data model described by Um et al. (2008).

Product Class

The product class acts as a container for all the components that constitute the product.

- *Root* – Identifies the root component of the product.
- *ListofComponentInstances* – A list comprising of all the components that make up the product.

Component Instance Class

The component instance class is used to identify and describe products, subassemblies and components. It plays a central role within the product model as it is used to represent every component instance within a product.

- *ObjectLotID* - A unique identifier of a component instance.
- *Parent* - Identifies the parent of the component instance.
- *DesignInfo* - Associates a Designed_Info class to the component or product, containing the design information
- *LifeCyclePhase* - A list of LifeCyclePhase classes, each relating to the specific life cycle phases, BoL, MoL and EoL.
- *ChildrenList* – List of child components relative the component instance.

Design Info Class

This class describes the product as it was designed at the BoL. This class provides generic information, however it can be expanded using the property class to include additional attributes.

- *Design ID* - The designated ID of the product design.
- *Type* - Classifies the product/component type (e.g. gearbox).
- *Manufacturer* – The name of the product OEM.
- *Model* - The name of product model.
- *PropertyList* – A list of property objects containing information related to the product

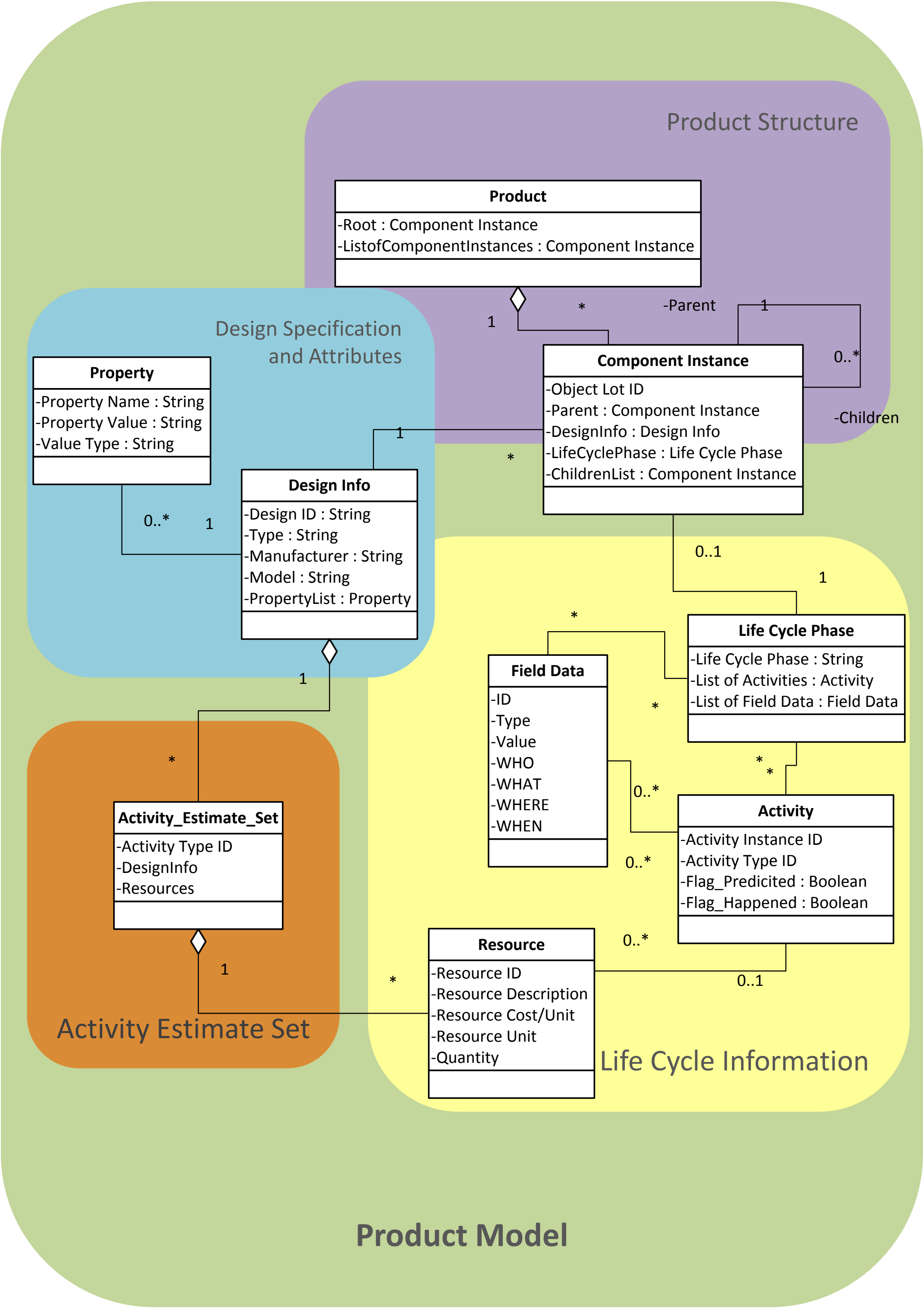


Figure 7-6 Product Data Model shown using a UML class diagram with the three main information areas

Property Class

This class is used as a way of adding particular attributes to describe the design of a product or component. These attributes are specific to a particular product type and therefore are listed within the generic As Designed Class.

- *Property Name* - The name of the product attribute (e.g. Power rating).
- *Property Value* - The value of the property (e.g. 220).
- *Value type* - The unit which the Property Value is given as (e.g. kW).

Life Cycle Phase Class

This class is used to identify at which stage in the product life cycle processes, activities and field data were collected.

- *Life Cycle Phase* – The name of the life cycle phase which is either set to Beginning of Life (BoL), Middle of Life (MoL) or End of Life (EoL).
- *List of Activities* – Contains a list of objects of class type *Activty*, which are associated with the life cycle phases.
- *List of Field Data* – Contains a list of objects of class type *Field_Data*, which are associated with the life cycle phases.

Activity Class

The activity class is used to represent recorded activities and events that occurred during the product's life cycle. This is used to represent historical job information obtained from the knowledge base database, such as remanufacturing activity costs.

- *Activity ID* - unique identifier for the historical remanufacturing activity.
- *Activity Type ID* - The ID for a particular activity such as 'Sand Blasting'.
- *Activity Cost* – The total recorded cost of the particular historical activity case.

Field Data Class

This class is used to represent measured data about a product or component. Examples of this include sensor data from the MoL phase, such as temperature or odometer readings. Additionally this can also be used to store EoL data from tests and inspections which take place during remanufacture. This class can be used within the cost estimation method to identify similarities between historical products for the case based reasoning analysis.

- *ID* - The unique ID of the recorded data.
- *Type* - Identifies the type of recorded data (such as odometer measurement).
- *Value* - The measurement value.

- *WHO* - Who made the measurement.
- *WHAT* – Provides additional information about what the field measurement was.
- *WHERE* - Where was the measurement taken.
- *WHEN* - When the measurement was taken.

Resource Class

The resource class is used to represent the resources consumed by an activity. Each resource is represented as an object and contains the following attributes;

- *Resource ID* - The unique identifier of a particular resource.
- *Resource Description* - The type of resource used (e.g. oil).
- *Resource Cost/Unit* - The cost rate of a resource (e.g. labour rate of £50/hour, 50 would therefore become the value).
- *Resource Unit* - The unit of measurement which is used to quantify the resource (e.g. labour rate is quantified by time so the unit would be hours).
- *Quantity* - The quantity of resource used by the activity in this historical instance.

Activity Estimate Set Class

This class is used to represent information obtained from the knowledge base regarding the estimated activity cost for a particular component, described in section 6.3.2.2.

- *ActivityTypeID* – The activity type ID.
- *ProductDesigninfo* – The ID of the product or component which the activity relates to.
- *Resources* – A list of resource objects required by the activity.

7.4.5 Process Model

The process model is used to represent the remanufacturing process as part of the case description, described in section 6.3.1.2. The model structure is shown in Figure 7-7 and comprises of ten classes discussed below.

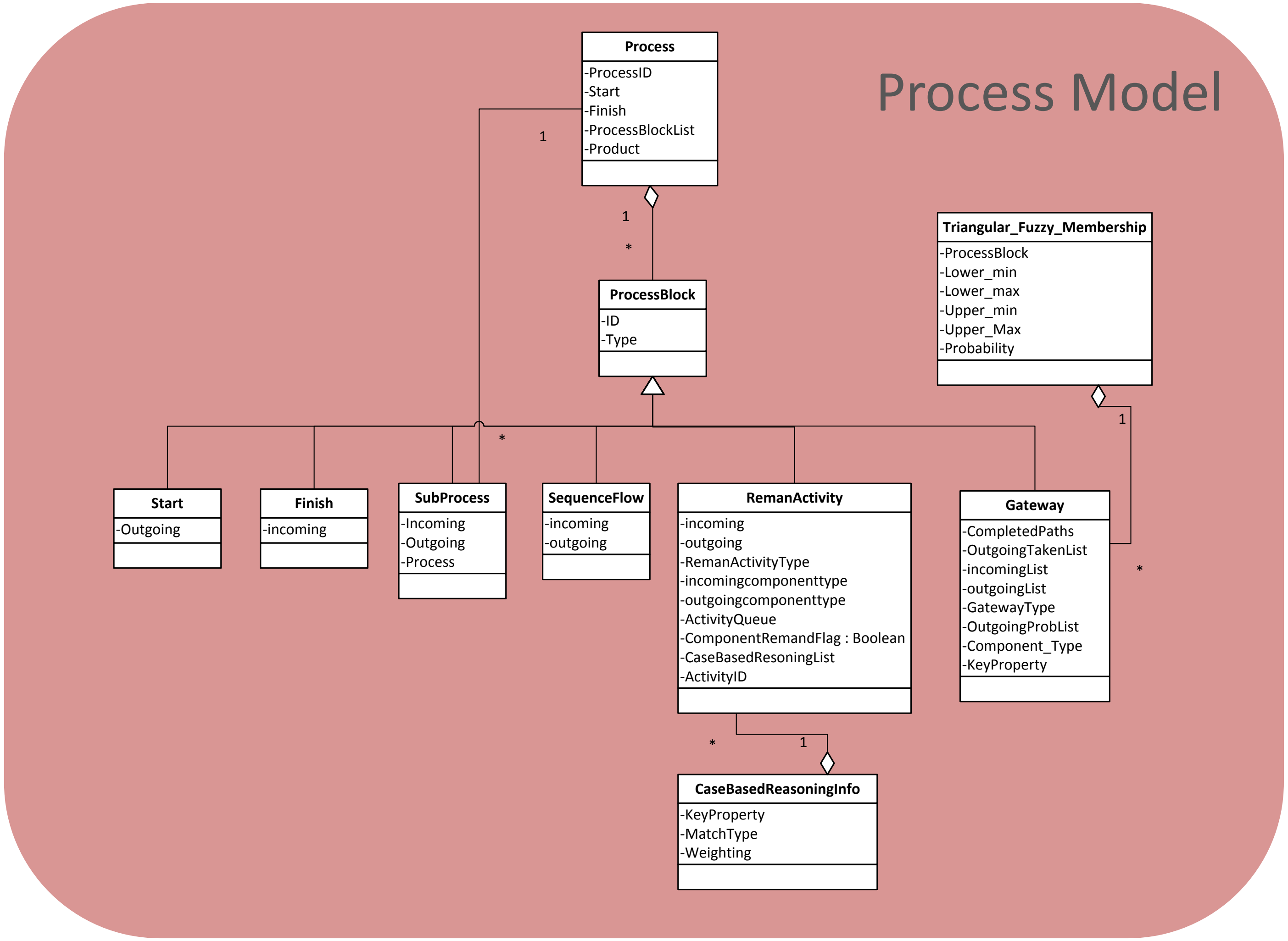


Figure 7-7 Process model represented in a UML class diagram

Process Class

The Process Class acts as a container of process blocks which make up the entire process.

- *ProcessID* - The unique identifier of the process.
- *Start* – Indicates which of the process blocks is the start.
- *Finish* – Indicates which of the process blocks is the finish.
- *ProcessBlockList* – A list containing objects of type ProcessBlock, which contains all of the process blocks associated with the process.
- *Product* – Indicates the product type associated with the process, e.g. gearbox.

ProcessBlock Class

This is a generic class to describe the fundamental elements that make up a process.

- *ID* - A unique ID for the ProcessBlock.
- *Type* - Signifies which particular type of process block object the ProcessBlock is representing. The types correlate to the name of the inherited classes.

Start Class

Represents a start process block and inherits the properties of the ProcessBlock Class.

- *Outgoing* – States the next ProcessBlock to follow the Start Block within the overall process.

Finish Class

Represents a finish process block and inherits the properties of the ProcessBlock Class.

- *Incoming* – States the ProcessBlock which occurs immediately before the Finish Block.

RemanActivity Class

Represents a remanufacturing activity and inherits the properties of the ProcessBlock Class

- *Incoming* – States the ProcessBlock which occurs immediately before the RemanActivity block.
- *Outgoing* – States the next ProcessBlock to follow the Start Block within the overall process.
- *RemanActivityType* - The type of remanufacturing activity the RemanActivity is representing which are listed in 6.2.1.1.1.
- *incomingcomponenttype* - The type of component which the activity is performed on.

- *outgoingcomponenttype* - The type of component at the end of the activity, which is important when dealing with assembly activities as incoming and outgoing component types will differ.
- *ComponentRemanedFlag* - A marker to determine if the component is considered remanufactured after the activity has occurred. This is useful for the cost estimation method in determining which of the component stores to place the product in after the activity has been conducted (used or remanufactured component store).
- *CasedBasedResoningList* –A list of *CaseBasedReasoningInfo* objects used to identify properties for which case based reasoning similarity should be assessed upon.

SubProcess Class

Represents a subprocess and inherits the properties of the ProcessBlock Class.

- *Incoming* - States the ProcessBlock which occurs immediately before the sub process.
- *Outgoing* - States the next ProcessBlock to follow the Subprocess.
- *Start* – Indicates which of the process blocks is the start.
- *Finish* – Indicates which of the process blocks is the finish.

SequenceFlow Class

Represents a sequence flow and inherits the properties of the ProcessBlock Class.

- *Incoming* - States the ProcessBlock which occurs immediately before the sequence flow.
- *Outgoing* - States the next ProcessBlock to follow the sequence flow.

Gateway Class

Represents a gateway and inherits the properties of the ProcessBlock Class.

- *Gatewaytype* - The type of gateway, which is either exclusive or parallel.
- *CompletedPaths* – An attribute used only by the parallel type. It is used only during the calculation process to determine how many paths have been completed, detailed in section 6.2.1.1.2.
- *OutgoingTaken* - – An attribute used only by the parallel type. It is used only during the calculation process to determine how many paths have been taken from the split gateway, detailed in section 6.2.1.1.2.
- *IncomingList* - The process blocks which occur immediately before the gateway.
- *OutgoingList* - States the next process blocks to follow the gateway.
- outgoingprobList - The probability of each outgoing path as a list of singles.
- *Component_Type* – A list of component types associated with each outgoing path from a parallel gateway.

- *KeyProperty* – Identifies which property is used within the product datamodel to affect the decision probability.

CasedBasedReasoningInfo class

This class is used to assist with the case based reasoning algorithm by storing information detailing which properties of the product affect the cost of a particular activity. Each class represents a single property associated to a particular activity.

- *KeyProperty* - A property within the class model for which the case based reasoning will be assessed upon.
- *MatchType* - The method required to assess the property similarity (e.g. semantic or fuzzy numerical).
- *Weighting* - The weighting the property (a value between 0 and 1).

Triangular_Fuzzy_Membership class

This class is used to signify a fuzzy memberships, shaped either in a triangular or quadrilateral form, between an outgoing gateway path and a specified key property. The following attributes are used to describe this fuzzy relationship.

- *ProcessBlock* – States the gateway which this membership function is associated with.
- *Lower_min* – The minimum value of the specified property, in which the membership probability is at a minimum.
- *Lower_max* – The minimum value of the specified property, in which the membership probability is at a maximum.
- *Upper_min* – The maximum value of the specified property, in which the membership probability is at a maximum.
- *Upper_max* – The maximum value of the specified property, in which the membership probability is at a minimum.
- *Probability* – The maximum probability value of the membership function.

7.5 Chapter 7 Summary

This chapter has detailed the software implementation of the cost estimation tool. The tool has been implemented as a web service BDSS, due to the integration within the PREMANUS project. The tool itself is contained within the service aspect of the web service. Three relational databases are used to capture and store information related to the product, process and activity costs.

The cost tool has been implemented using an object oriented structure, which has allowed the abstraction of real life objects into the code design. The code has been structured into three key areas; the cost estimation method, the product model and the process model. The cost estimation method contains nine classes used to represent the design and algorithms described in chapter 6. The product and process model structures allow the data to be extracted from the database sources and represented within an object structure for use by the cost estimation method. Detailed explanations of the classes, their attributes, methods and relationships with each other are also provided within this chapter.

8 Validation

8.1 Introduction

Validation is required to demonstrate the applicability of the developed software tool for its intended purpose. The requirements for the cost estimation tool were defined within Chapter 4, based upon the findings of an extensive literature review and discussions with industry. To validate the design and implementation, carried out within Chapter 6 and 7 respectively, the developed software tool has been executed using specific case study examples to determine and demonstrate that it meets the evaluation criteria defined within the requirements specification.

To demonstrate the specification requirements, two case studies have been used to exhibit the use of the tool. An explanation of the rationale for each case being selected and how the information was collected is given within the following methodology section. Each case study is then described, including a description of how the cost estimation tool could be used as part of their business process. Demonstrative examples are then provided for each of the case studies as a means of validating the cost estimation tool against the specification requirements. In total three examples are shown, one for the first case study and two for the second.

The chapter concludes with a discussion justifying whether the requirement specifications are met and identifying further work to develop the tool.

8.2 Methodology

Two case studies are used to demonstrate the application and functionality of the tool relative to the specification requirements outlined in Chapter 4 and shown in Table 8-2. These cases have been chosen as they complement the validation process due to their contrasting nature. Differences in product, process and information sources enable the generic functionality of the software tool to be demonstrated (Requirement 3), whilst differing levels of uncertainty within the data of the cases highlight the ability of the tool to meet the requirements outlined in Requirement 2.

The first case represents a remanufacturing business containing relatively low uncertainty. This is due to the facility being owned by the OEM, which enables information about the product, such as its design structure and EoL condition to be known prior to remanufacture commencing. Additionally due to the relatively high volume of products remanufactured and number of years it has been established, the relationships between the activity costs for a particular component are well known. The second case represents a remanufacturing business operating under high uncertainty. The business is independent of the OEM, thus information about each product is limited. Condition of the products may or may not be known, and additionally due to the low volume of products remanufactured and the high variability of product types, there is less understanding of the activity costs.

These case studies have been developed from close collaboration within the PREMANUS project. Information has been collected by interviews with key members of staff within the remanufacturing facilities, as highlighted within Table 8-1. Key information has been collected in helping to understand the business process, the remanufacturing process, the key constraints and issues faced by each remanufacturer.

Table 8-1 A summary of the two case studies used within this validation section

	Case 1	**Case 2**
Staff Interviewed	Senior member of the research team associated with the plant	Remanufacturing facility management team, Senior management
Visited Remanufacturing Facility	No	Yes
Product	Engine	Gearbox
Level of uncertainty	Low	High
Remanufacturing Process	Yes	Yes
Activity Costs	Yes (From expert opinion)	No
Similarity Scores	No	Yes (Generated data)
Historical Case Data	No	Yes (Generated data)
Gateway Decisions	Yes (From real data)	Yes (Generated data)

Product and process models have been developed through interviews and data available from the cases, such as inspection reports (see Appendix B). For Case 1, activity costs have been collected through interviews with staff, whilst gateway decision logic has been based upon data collected by the business. For Case 2, limited cost information was available due to a lack of data collected by the business. Therefore, information regarding historical job records and decision logic have been created to demonstrate the software tool's functionality.

Three examples have been created to demonstrate the functionality of the cost and risk estimation tool relative the specification requirements, outlined within Table 8-2. Example A is based upon Case 1, whilst Examples B and C are based upon Case 2. Examples B and C demonstrate a simplified and a detailed representation of Case 2 respectively. This allows Requirement 2.1.1. to be demonstrated within example B. Selected aspects of each example are shown within this Chapter to highlight how the software tool has met the specification requirements. Details of each example can be found in Appendix A.

Table 8-2 Functional requirements list from Chapter 4 with the example demonstration link

ID	Requirement description	Functionality demonstrated in example;		
		A	B	C
1.	**Cost Calculation** - The system shall estimate the economic cost of remanufacturing a particular product based upon the resource requirements under the following conditions; • Remanufacturing is treated as a single job lot (i.e. a lot size a 1). • The remanufacturing process begins as the product arrives at the factory and finishes upon its departure, i.e. logistical costs are not considered • The cost of storage is not considered within the estimate	✓	✓	✓
2.	**Risk and Uncertainty** - The system shall estimate the economic risk of remanufacturing a particular product due to the following uncertainties;			
2.1.	**Product Design** – The system shall allow calculation of cost when uncertainties regarding the product design are present. The uncertainties refer to the following specific product design aspects;			
2.1.1.	*Structural Layout (BoM)* – When the number and type of components making up the product are unknown.		✓	
2.1.2.	*Key Attributes* – When key attribute information, such as product weight, is unknown.		✓	✓
2.2.	**Product Condition** – The system shall allow calculation of cost when uncertainties regarding the product condition are present. The uncertainties refer to the following specific types;			
2.2.1.	*Unknown Condition* – When no information exists regarding the information of the product condition.		✓	✓
2.2.2.	*Ambiguous condition* - When information related to the product condition does not always correlate to an exact process outcome.	✓		✓
2.3.	**Process –** The system shall account for uncertainties related to the remanufacturing process within the cost estimation for the following factors;			
2.3.1.	*Inherent process variations* – Where inherent variations may occur from one process to another when all other given factors are equal, such as disassembly time.		✓	✓
2.3.2.	*Process knowledge uncertainties* – When information about specific remanufacturing activities is unknown due to a lack of experience.		✓	✓
3.	**Generic Functionality** – The system shall be robust to ensure that a generic remanufacturer can use the tool specifically for their application. In order to comply with this requirement, the following specific sub elements have been outlined;			
3.1.	**Product Design** – The system shall provide a generic product model, in which specific products can be described. Explicitly it is comprised of the following requirements;			
3.1.1.	*Product Types* – The product model shall allow for multiple types of product and component to be described. It should allow for specific attributes which may be unique to particular products to be described.	✓		✓
3.1.2.	*Variations within product types* – The product model shall also allow variations between products types to be described, such as the number and type of components that it may contain.			✓
3.2.	**Process Design** – The system shall provide a generic process information model, in which specific remanufacturing process can be described. The process shall allow the generic remanufacturing activities to be described, as shown in section 2.3.2.1. The process should allow the possible permutations that may occur to be described.	✓		✓
3.3.	**Cost information –** The system shall enable cost information from multiple sources to be used.			✓

8.3 Case 1

8.3.1 Introduction (Case 1)

The first case study is of a dedicated remanufacturing facility of automotive engines for domestic and commercial vehicles. The facility is owned by a large parent company which owns several OEMs of domestic and commercial vehicles. The facility remanufactures approximately 3000 engines per year from 3 of the OEMs within this group, as part of their aftermarket spare parts business. The core aims of the facility are to reduce the need to buy new spare parts and increase the salvage rate of the factory.

8.3.2 Business Scenario (Case 1)

Cores are currently supplied to the factory thorough an existing dealer network which interacts with customers. The plant currently offers a fixed price for these cores, irrespective of condition. On arrival at the remanufacturing facility, cores are assessed and classified based upon their condition. Using a number of factors, including cost, current inventory levels and demand, a decision is required for the remanufacturing strategy of the core. Cores are then either stored, remanufactured immediately, or disposed.

A current issue for the business is ensuring that high quality cores are sourced into the facility in order to reduce the cost and increase the salvage rate for remanufacture. This is currently being hindered by the fixed price policy for product cores. Dealers who receive used products from customers are not obliged to send these directly to the remanufacturing facility. In some cases, when the cores are returned in good condition, dealers can seek better offers than can be received from the remanufacturing plant. The net effect of this is that the remanufacturing plant often misses out of high quality cores which are more desirable to remanufacture. Additionally by paying a fixed price for cores, those of lower quality are often overpriced relative to their actual value.

To combat this issue the remanufacturing facility would like to introduce a bespoke quotation system, which estimates the value of a specific engine core. To enable this, information regarding the products' MoL must be collected in order to indicate the condition in which it is returned. This can be facilitated using an on board computer system which records sensor data monitoring the engine. Using existing relationships regarding the sensor data and product condition, the cost of remanufacturing can be calculated using the cost and uncertainty tool presented within this thesis.

8.3.3 Cost and Uncertainty Calculation (Example A)

The software tool is now implemented for the above case study. The first step is to develop the product and process models which will be used to conduct the calculation.

8.3.3.1 *Product Model (Example A)*

To demonstrate the software tool, a single engine type will be used that is commonly remanufactured within the factory. The structure of the engine and its key components are illustrated within Figure 8-1.

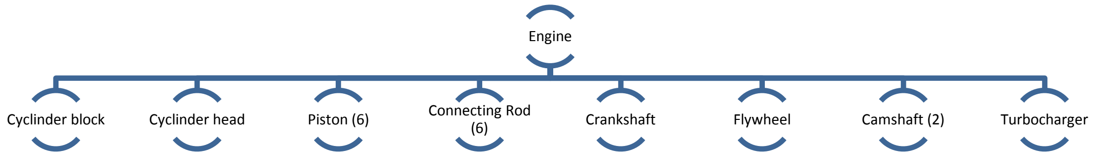


Figure 8-1 Hierarchal representation of the DUC engine used within the case example

As this example demonstrates low levels of uncertainty, activity costs later will be determined through matching component ID's with a particular activity. The information requirements for each component within the product model are shown in Table 8-3, with examples for the engine and piston.

Table 8-3 Product model requirements for example A, only the Engine and Piston are shown here

Component Instance	Component Design ID	Component Type	Residual Life Value (%)	Parent Component
Engine_A	DUC_Engine	Engine	60	N/A
Piston_A	DUC_Piston	Piston	40	Engine_A

The residual life value is a metric used by Case 1 to identify MoL condition of the engine and its components. These values are calculated based upon MoL data captured by sensors on the engine. For the purpose of this example these raw MoL readings are used to calculate a single residual life value, which is determined by a mathematical model developed by the OEM in question. For the purpose of demonstrating the cost and risk estimation tool this calculation can be treated as a black box, as shown in Figure 8-2, with only the residual life value being used within this example.

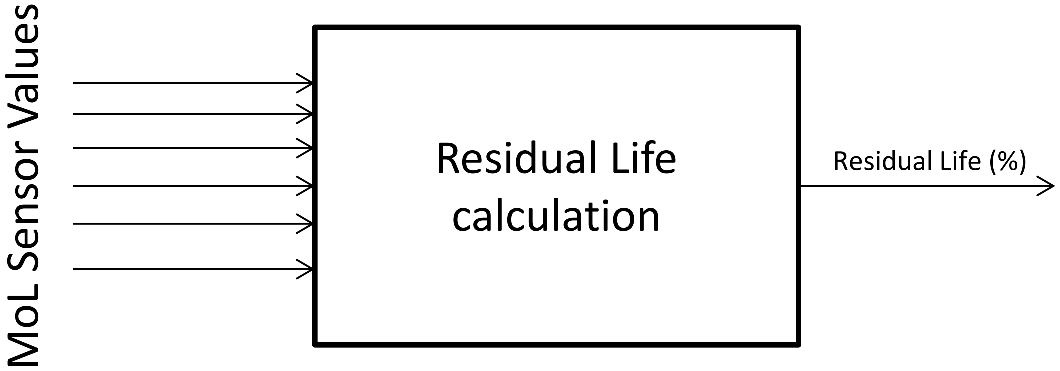
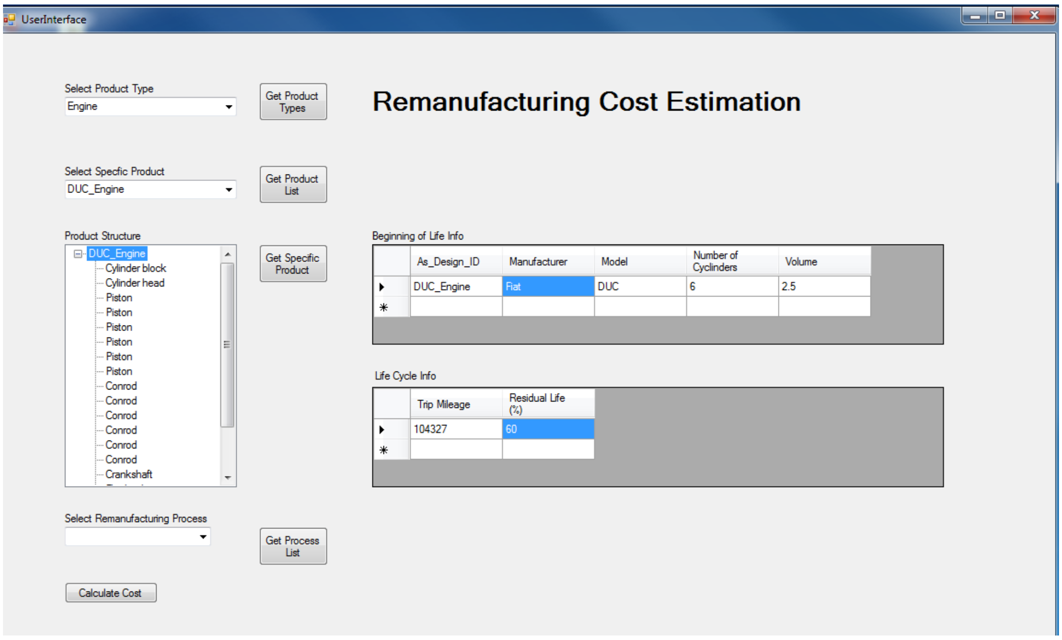


Figure 8-2 Calculation of residual life metric illustrated with a black box approach

The information required to construct the product model is then input into the user interface ready to be used within the cost calculation tool, as shown in Figure 8-3.



Select Product Type: Engine

Select Specfic Product: DUC_Engine

Product Structure:
- DUC_Engine
  - Cylinder block
  - Cylinder head
  - Piston
  - Piston
  - Piston
  - Piston
  - Piston
  - Piston
  - Conrod
  - Conrod
  - Conrod
  - Conrod
  - Conrod
  - Conrod
  - Crankshaft

Select Remanufacturing Process:

Beginning of Life Info

	As_Design_ID	Manufacturer	Model	Number of Cyclinders	Volume
▶	DUC_Engine	Fiat	DUC	6	2.5
*					

Life Cycle Info

	Trip Mileage	Residual Life (%)
▶	104327	60
*		

Figure 8-3 Product model displayed within the user interface

To visualise this information within the process model, an object representation of the engine is shown in Figure 8-4. An additional property of swept volume has been added to demonstrate how such information can be represented within the product model. Whilst that information is not required for this specific example, it highlights how the product model can represent a range of different product types, a requirement of the tool outlined in Requirement 3.1.1.

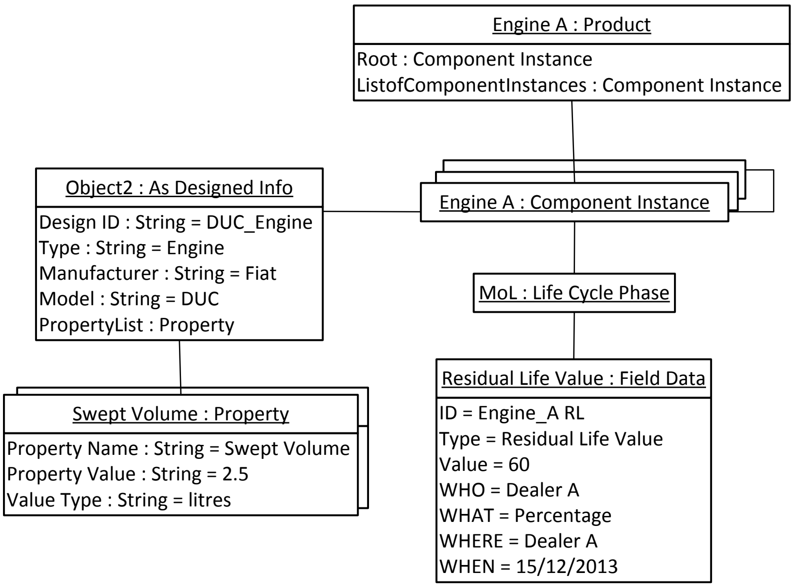


Figure 8-4 Object representation of the engine within the product model

8.3.3.2 Process Model (Example A)

The information used to generate the remanufacturing process model is based upon documents produced from discussions and interviews with managerial and research personal within the company. These interviews were conducted by partners within the PREMANUS project and distributed within the group. The process models were then created and verified by a research manager affiliated to the remanufacturing business. Two of the processes have been included here as examples to demonstrate the level of detail within the model. The two processes shown in the main body of the text are the high level engine and piston remanufacturing processes shown in Figure 8-5 and Figure 8-6 respectively. The full process can be found within Appendix A. The full process model is described within 9 process flows, 1 at the highest level (Figure 8-5) and 8 sub processes, one for each of the component types. The process information was input into the process model via the Microsoft Access database. An object representation of the piston remanufacturing sub process is shown in Figure 8-7, highlighting how the information is contained within the process model structure. The ability to represent the actual process within process model helps to demonstrate the Requirement 3.2.

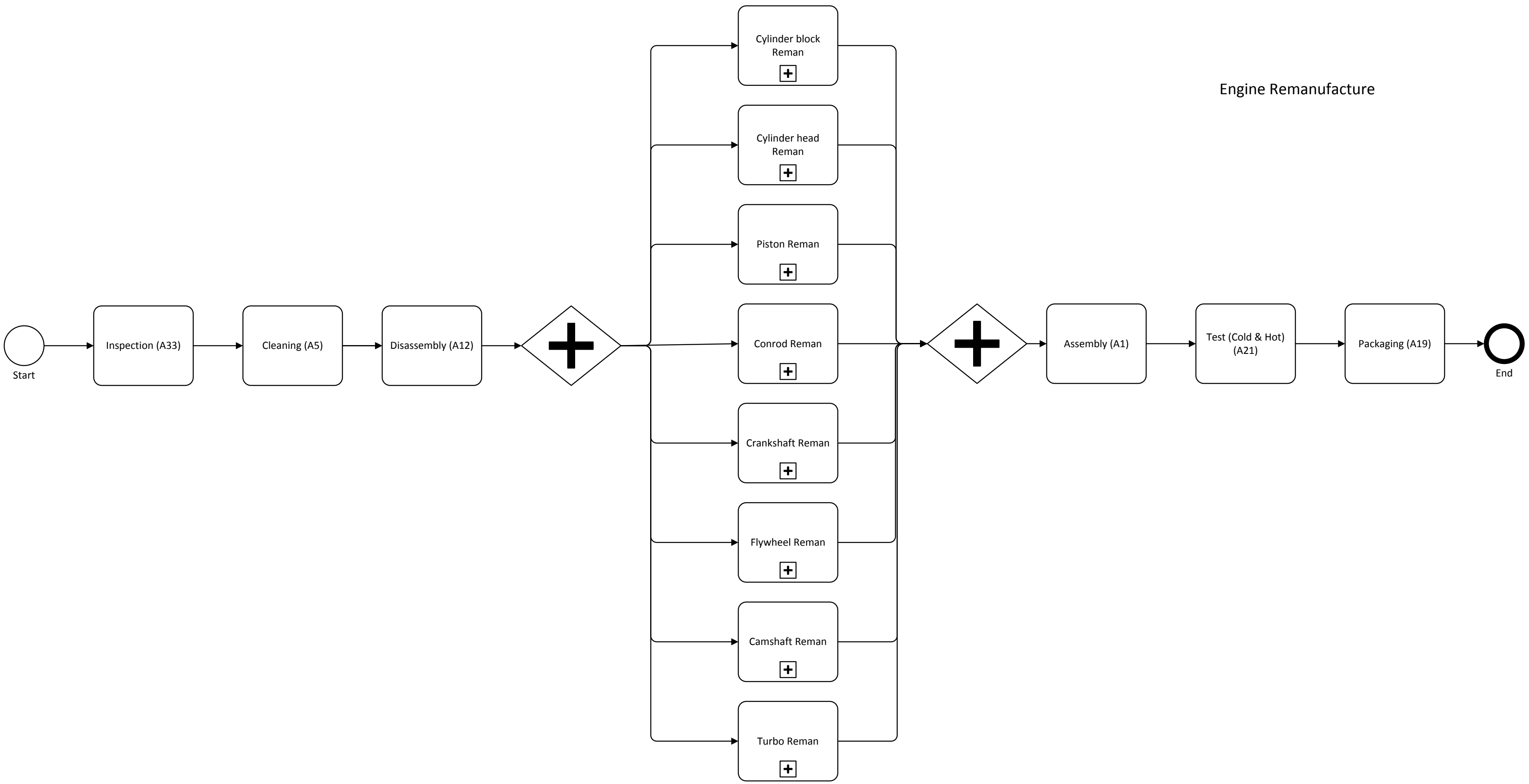


Figure 8-5 High level BPMN diagram of the engine remanufacturing process

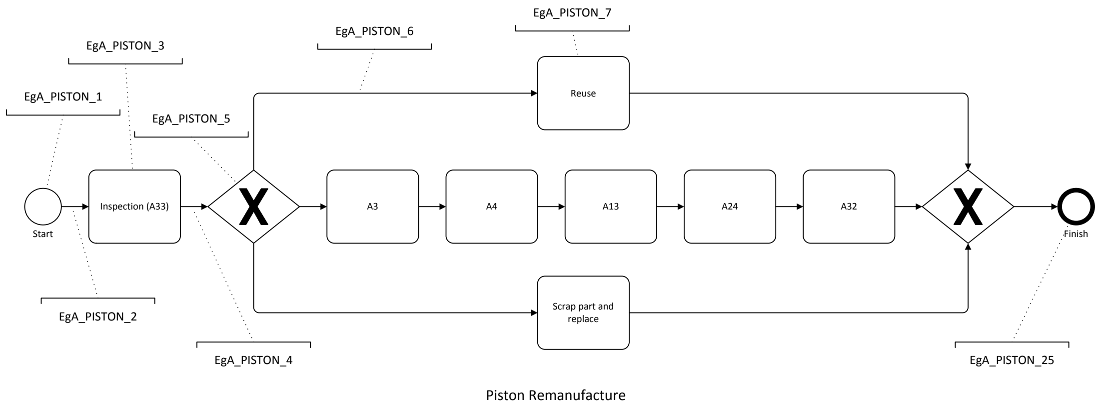
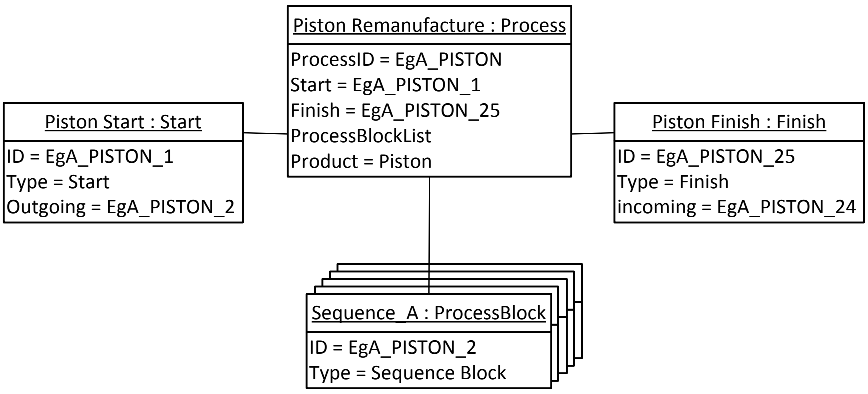


Figure 8-6 Expanded sub process of piston remanufacture with annotated id's for selected process blocks

Table 8-4 List of some of the process blocks contained within the Piston Remanufacture process

Id	**Type**
EgA_PISTON_1	Start
EgA _PISTON_2	Sequence Block
EgA _PISTON_3	Activity
EgA _PISTON_4	Sequence Block
EgA _PISTON_5	Gateway
EgA _PISTON_6	Sequence Block
EgA _PISTON_7	Activity


Piston Remanufacture : Process
ProcessID = EgA_PISTON
Start = EgA_PISTON_1
Finish = EgA_PISTON_25
ProcessBlockList
Product = Piston

Piston Start : Start
ID = EgA_PISTON_1
Type = Start
Outgoing = EgA_PISTON_2

Piston Finish : Finish
ID = EgA_PISTON_25
Type = Finish
incoming = EgA_PISTON_24

Sequence_A : ProcessBlock
ID = EgA_PISTON_2
Type = Sequence Block

Figure 8-7 Object representation of the Piston remanufacturing process (Note not showing detail below the process block level)

A triangular fuzzy membership function has been used to model the decision at the exclusive gateway within the piston remanufacturing sub process and is displayed in Figure 8-8. The relationship between the outcome of this decision and the residual life value for the piston was identified through data recorded by the business. It was noted however that the accuracy of the residual life value in indicating the outgoing path is not perfect, thus containing some ambiguity. The fuzzy membership is therefore a suitable method of describing both the relationship and the degree of uncertainty contained within, thus fulfilling Requirement 2.2.2. The values of the fuzzy memberships have been determined based upon sample data and negotiations with the business.

Values of each membership are found in Table 8-5, whilst the object diagram in Figure 8-9 depicts how the information is described within the process model.

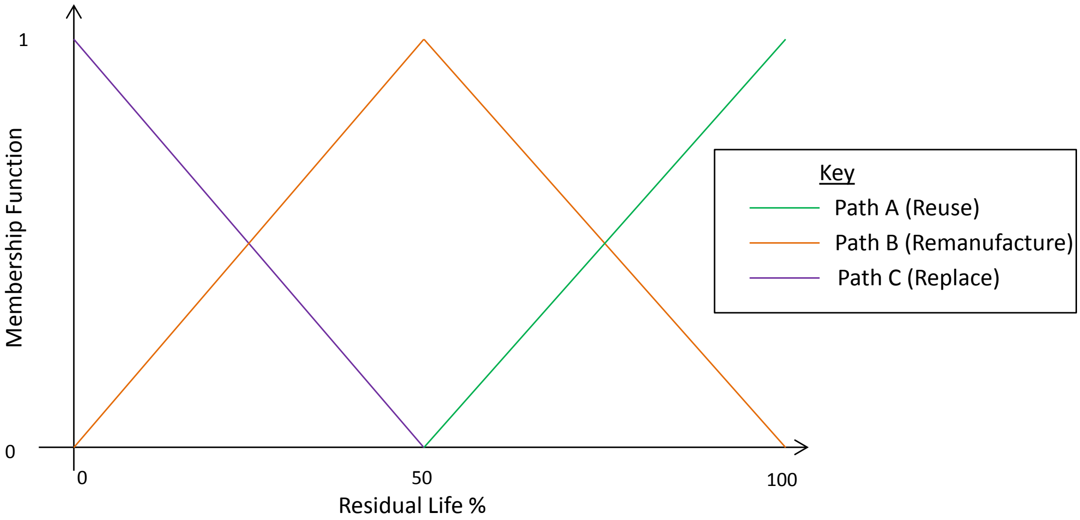


Figure 8-8 Fuzzy membership function used for the Piston Remanufacture process gateway

Table 8-5 Input values to describe the membership functions

Fuzzy membership attribute	**Outgoing Path**		
	A (Reuse)	**B (Remanufacture)**	**C (Replace)**
Lower Min	50	0	0
Lower Max	100	50	0
Upper Max	100	50	0
Upper Min	100	100	50

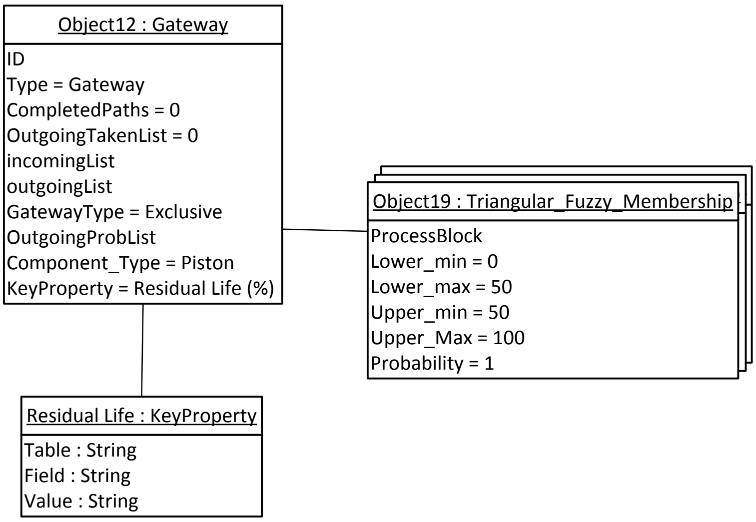


Figure 8-9 Object representations of the exclusive gateway and the fuzzy triangular memberships

8.3.3.3 Activity Costs and Probability (Example A)

Within this example we assume that a mean cost for each individual activity is known for each component type, as shown in Table 8-6. This is a fair assumption due to the relatively high volume and limited types of engines that are remanufactured at the facility which means that it has been possible to draw reliable statistics from historical data. A labour rate of £50/hour, machine rate of £60/hour and Piston replace cost of £20 were used for the calculations. Some activity names have been removed for confidentiality reasons.

Table 8-6 Resources required for each activity for each component

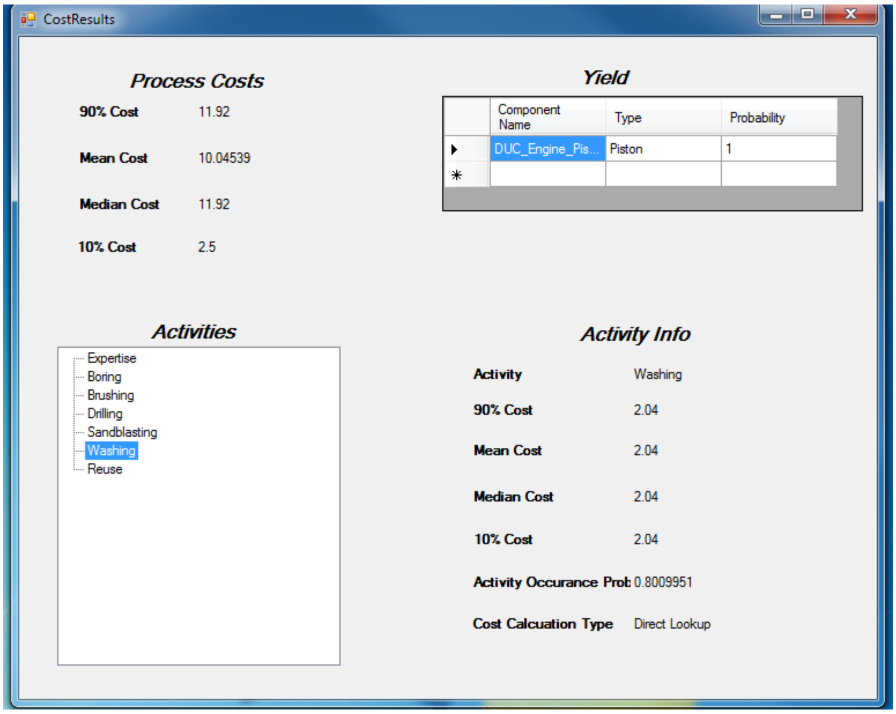
Activity	Engine			Piston		
	Labour (h)	Machine (h)	Replacement	Labour (h)	Machine (h)	Replacement
A1 Assembly	1.03	0	0	-	-	-
A3	-	-	-	0	0.015	0
A4	-	-	-	0.018	0	0
A5 Cleaning	0	0.3	0	-	-	-
A12 Disassembly	1.8	0	0	-	-	-
A13	-	-	-	0	0.07	0
A19 Packaging	0.3	0	0	-	-	-
A21 Test	0	1.92	0	-	-	-
A24	-	-	-	0	0.023	0
A32	-	-	-	0	0.034	0
A33 Inspection	0.11	0	0	0.05	0	0
Reuse	-	-	-	0	0	0
Scrap Part & Replace	-	-	-	0	0	1

8.3.3.4 Cost Calculation (Example A)

Data was entered in the calculation software to determine cost and risk metrics. The residual life value was varied from 0% to 100%, with 10% increments. For one calculation no residual life information was given to demonstrate how uncertainty is dealt with. Full results for the piston remanufacture can be found in Table 8-7, whilst the results for 60% residual life are displayed within the user interface within Figure 8-10. The completion of the cost calculation for the engine remanufacture fulfils the requirement 1, whilst the result with no information partially fulfils requirement 2.2.1.

Table 8-7 Results for Piston remanufacture with varying residual life

Residual Life (%)	Mean Cost (£)	10th Percentile Cost (£)	90th Percentile Cost (£)
0	22.5	22.5	22.5
10	20.7	11.9	22.5
20	18.5	11.9	22.5
30	16.3	11.9	22.5
40	14.3	11.9	22.5
50	11.9	11.9	11.9
60	10.4	2.5	11.9
70	8.5	2.5	11.9
80	6.6	2.5	11.9
90	4.6	2.5	11.9
100	2.5	2.5	2.5
No Information	11.9	2.5	22.5



Process Costs

90% Cost 11.92

Mean Cost 10.04539

Median Cost 11.92

10% Cost 2.5

Yield

	Component Name	Type	Probability
▶	DUC_Engine_Pis...	Piston	1
*			

Activities

- Expertise
- Boring
- Brushing
- Drilling
- Sandblasting
- Washing
- Reuse

Activity Info

Activity Washing

90% Cost 2.04

Mean Cost 2.04

Median Cost 2.04

10% Cost 2.04

Activity Occurance Prob 0.8009951

Cost Calcuation Type Direct Lookup

Figure 8-10 Cost results output to the user interface, for Piston remanufacture with a reusability value of 60%

8.4 Case 2

8.4.1 Introduction (Case 2)

The second case study is a small start-up facility for remanufacturing wind turbine gearboxes. The facility is a subsidiary of a major bearing manufacturer, whose products are widely used within the wind turbine industry. The company already has a presence within the wind turbine aftermarket sector, with an established condition monitoring service that alerts turbine owners to potential maintenance requirements through live sensor monitoring. The company decided to expand their aftermarket presence within the wind turbine sector by establishing the gearbox remanufacturing facility. The remanufacturing business operated on a trial basis from 2010 until the end of 2012.

8.4.2 Business Scenario (Case 2)

The remanufacturing business operates a 1 to 1 service, in which the customer retains ownership of the gearbox throughout. The full business process is shown in Figure 8-11. Customers will either contact the remanufacturing business asking for an estimation, or if the wind turbine is using the condition monitoring system and a problem is detected the company will alert the customer to a potential problem and quote the cost of remanufacturing. Data is then collected about the wind turbine and the gearbox which is then used to generate an indicative offer.

The initial quotation is indicative and not a legally binding agreement. If the quotation is acceptable the customer will then pay a fixed price for the company to disassemble and inspect the product at the remanufacturing facility. This inspection is conducted in two stages; the first is a preliminary visual inspection to identify major faults which would make remanufacturing unviable, once this stage is passed a more detailed inspection is conducted. Once this second detailed inspection is conducted a firm quotation is then offered to the customer to remanufacture the gearbox.

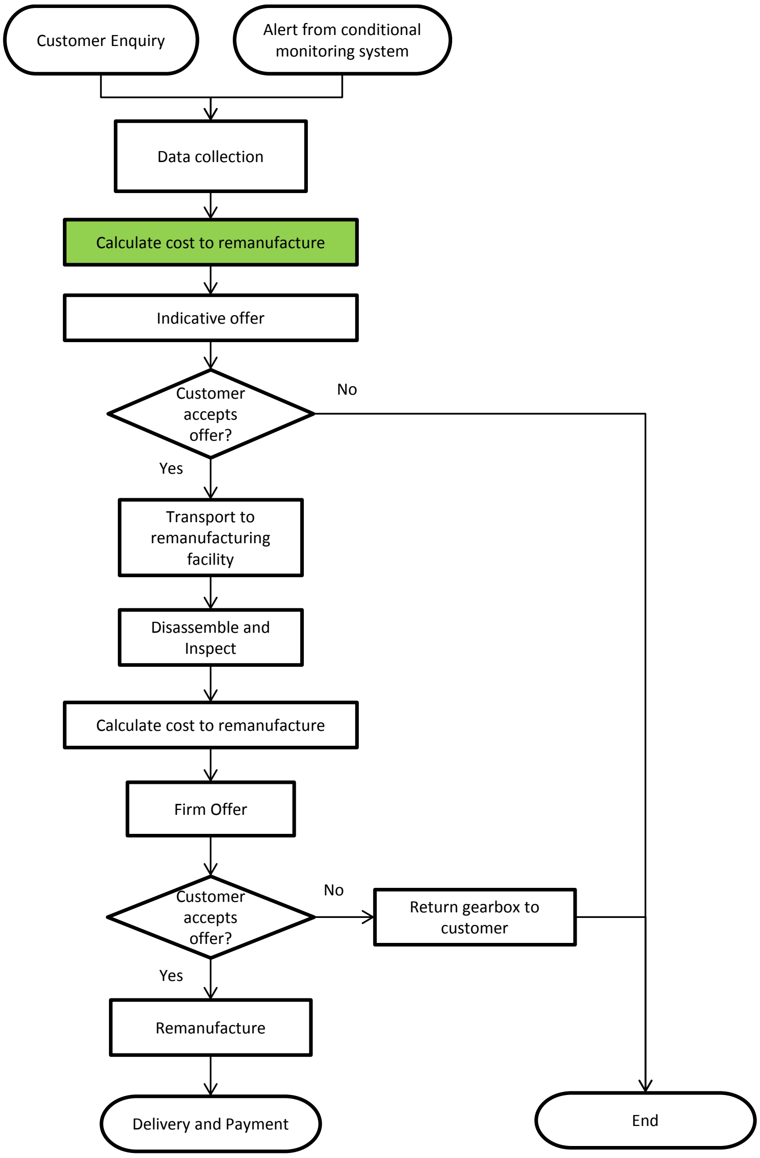


Figure 8-11 The business process for Case 2, with the cost estimation process highlighted in green

As with Case 1, a major challenge is estimating the cost of remanufacturing a gearbox. However, the uncertainty present in this case study is much greater than in the first, in particular because of the need to understand product type and structure. As the business is independent from the gearbox OEM, information relating to the product to be remanufactured is supplied by the customer. The detail in this information will vary significantly between customers. Even when complete product information is available, it can be difficult to accurately predict the effect on the remanufacturing cost due to the limited understanding between the product and the required activity resources. This is because the business dealt with a much smaller volume of products than case 1, with around 20 gearboxes per year. This, combined with the relatively large product variety of gearbox manufacturers and models, has made it difficult to accurately predict the resources required for each activity for a particular product model, which was used within Case 1. Instead the business must rely upon the combined knowledge generated from all historical cases in order to predict resource requirements.

8.4.3 Cost and Uncertainty Calculation (Case 2)

Due to the limited understanding of the resources required to conduct an activity for a particular product or component within this case study, Requirement 2.3.2 can be demonstrated using the case based reasoning method of determining an activity cost. Furthermore, due to the varying levels of information uncertainty about the product being considered for remanufacture, the robustness of the tool in handling uncertain product information (Requirement 2.1.2 and 2.2.1) can be demonstrated. Two contrasting examples have been developed with varying product uncertainty to demonstrate the functionality of the tool. Example B examines a gearbox with extreme uncertainty regarding the product structure. This illustrates the ability to simplify the product (Requirement 2.1.1.) and process model, although at the expense of estimation accuracy. Example C highlights a more complex calculation with a mixture of uncertainty present. This utilises all the key functionality of the tool, including how the algorithms developed can identify the correct costing method (Requirement 3.3.) and how different product structures can be used for the same process model (Requirement 3.1.2.).

8.4.4 Example B

8.4.4.1 Product Model (Example B)

Example B demonstrates a gearbox with limited information about its overall structure. This is modelled simply as a single gearbox component, without additional subassemblies and components. To keep this example simple, only three attributes shall be used to describe the gearbox, shown in Table 8-8. Additionally four product examples are shown each with varying amounts of information uncertainty. The effects of the uncertainty upon the cost and risk results are shown at the end of this section. An example of how this information is displayed within the product model is also shown in Figure 8-12.

Table 8-8 Information requirements for gearbox product model, with four product examples showing varying amounts of uncertainity

	Manufacturer	**Power Rating (MW)**	**Condition**
Gearbox_A	Eickhoff	1.3	2
Gearbox_B	Eickhoff	1.3	*Unknown*
Gearbox_C	Eickhoff	*Unknown*	*Unknown*
Gearbox_D	*Unknown*	*Unknown*	*Unknown*

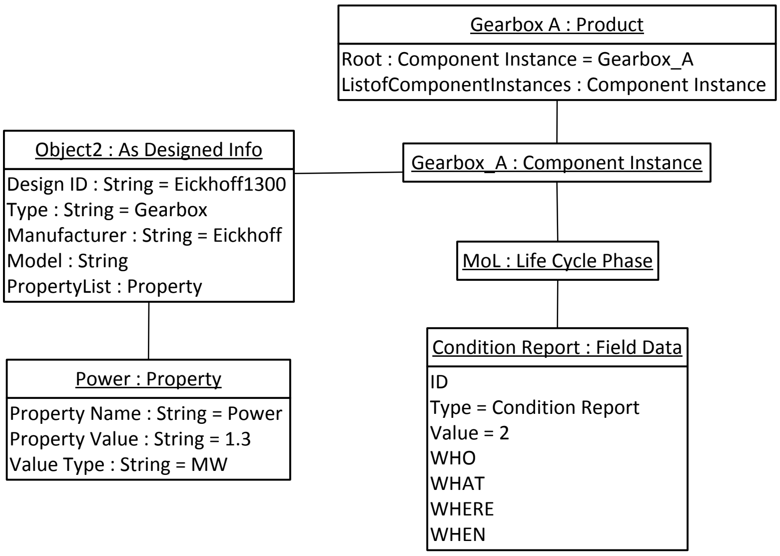


Figure 8-12 The depiction of the gearbox as an object within the product model structure

8.4.4.2 Process Model (Example B)

As the product structure is at a single component level a simplified process model is required. Parallel gateways are not required as subassemblies and components are not exposed. Detailed activities are grouped in to high level activities resulting in the simple linear process model that does not require exclusive gateways, as shown in Figure 8-13.

Figure 8-13 Process diagram for example B

Activity cost information is contained within historical job records. Every time a gearbox is remanufactured, information about the costs incurred for each activity are recorded along with information about the gearbox. This differs to example A, in which cost information was determined through interviews to identify particular costs for products and components. Costs for particular activities are then determined through the case based reasoning algorithm, which compares the similarity of previous job records to that of the new target case. In order for this to take place a set of similarity attributes are defined for each activity, as shown in Table 8-9 for Disassembly and Inspection. An object representation is also shown in Figure 8-14 to depict how the information is contained within the process model structure.

Table 8-9 Similarity attributes for the Disassembly and Inspection activity

Attribute	**Weighting**	**Match Type**
Manufacturer	1	Semantic
Power	0.6	Number
Condition	0.1	Number

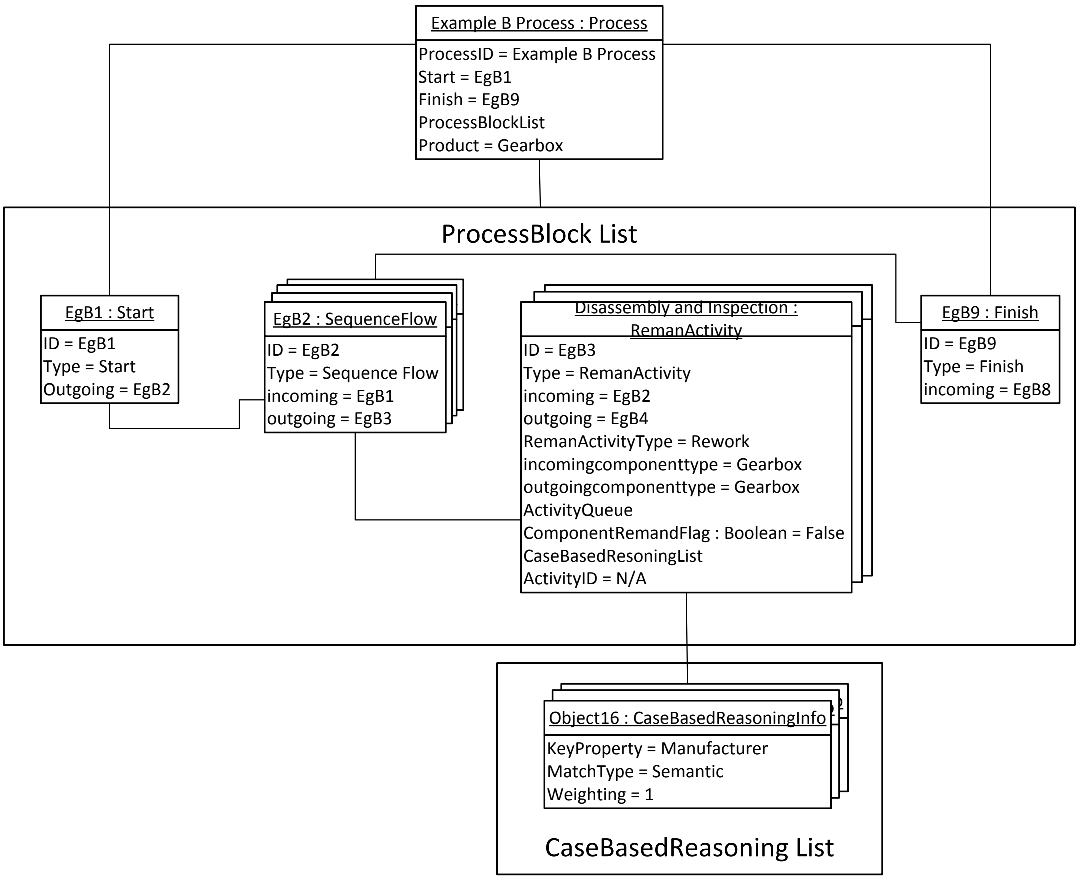


Figure 8-14 Object diagram showing the entire remanufacturing process for example B

8.4.4.3 Historical Job Records (Example B)

To enable the case based reasoning to be conducted, a set of historical job records are required, which can be used to derive the required activity cost. Unfortunately due to the short period of time the gearbox remanufacturer was in business, only three partial cases were collected. However, to demonstrate the application of this tool further cases have been created, as seen in Table 8-10. This information is stored within a relational database ready to be queried by the tool.

Table 8-10 Sample historical case data for Disassembly and inspection

	Manufacturer	**Power (MW)**	**Condition**	**Total Cost**
Gearbox_1	Eickhoff	1.0	4	£9,605
Gearbox_2	Eickhoff	1.0	5	£10,478
Gearbox_3	Eickhoff	1.5	1	£12,375
Gearbox_4	ZF	1.5	1	£15,850
Gearbox_5	Eickhoff	1.7	3	£15,582
Gearbox_6	ZF	1.8	3	£18,344
Gearbox_7	Bosch/Rexroth	1.8	4	£19,444
Gearbox_8	Bosch/Rexroth	1.8	5	£17,772
Gearbox_9	Eickhoff	2.0	3	£17,698
Gearbox_10	ZF	2.0	3	£19,868
Gearbox_11	Bosch/Rexroth	2.1	1	£19,444
Gearbox_12	Eickhoff	2.1	1	£16,865

8.4.4.4 Cost and uncertainty Calculation (Example B)

Cost calculation was performed using the product and process models, along with the historical job cases outlined above. Results from the disassembly activity are numerically and graphically displayed in Table 8-11 and Figure 8-15 respectively. The results demonstrate how the tool can perform cost estimation for products with limited information (Gearbox_D), all be it at the expense of increased risk metrics within the results. The results demonstrate the ability of the tool to firstly calculate cost and risk metrics with complete information (Requirement 1), and also under uncertain information within the product information (Requirement 2.1.2.) and with unknown product condition (Requirement 2.2.1.).

Table 8-11 Cost and Risk results from Example B for the disassembly and inspection activity

Number of iterations	**Mean Cost (£)**	**10th Percentile (£)**	**90th Percentile (£)**	**Range (90th-10th) (£)**
Gearbox_A	13843	9854	17833	7978
Gearbox_B	14000	9891	18108	8217
Gearbox_C	15120	10707	19532	8826
Gearbox_D	16088	11778	20398	8620

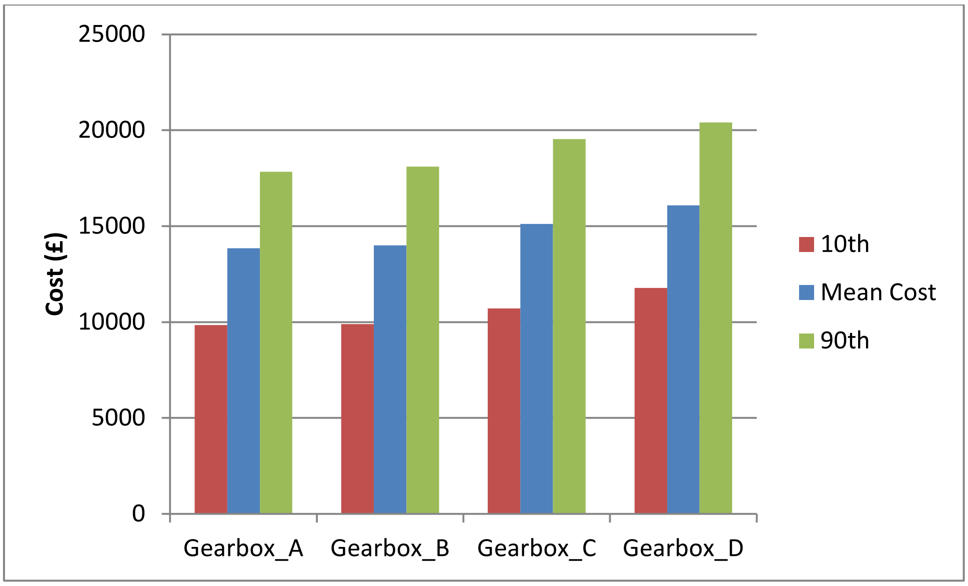


Figure 8-15 Example results for gearbox disassembly and inspection for each of the examples

8.4.5 Example C

8.4.5.1 Product Model (Example C)

For Example C the detail of the product model is shown in much greater depth, with all key components and subassemblies listed. To demonstrate the robustness of the process model relative to varying product structures (Requirement 3.1.2), two different gearbox configurations are presented, as found within the wind turbine industry. Information about each gearbox was collected using condition reports conducted by the customer. One gearbox comprises of two planetary and one parallel reduction stages, whilst the second contains one planetary and two parallel reduction stages, shown in Figure 8-16 and Figure 8-17 respectively. The information recorded for each component is not always complete, with some information unknown such as gear diameter. This demonstrates the ability of the tool to generate a cost with missing and incomplete information. An example of the information available for the bearings in first planetary stage of Gearbox 1 is shown in Table 8-15.

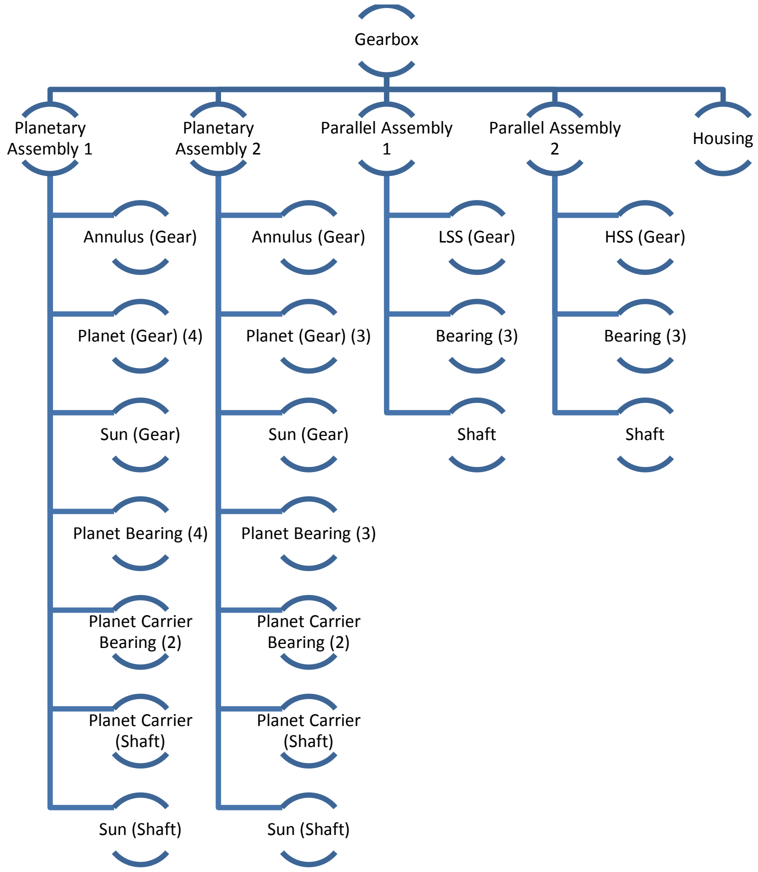


Figure 8-16 Gearbox 1 BoM and hierarchal structure of 2 stage planetary and 1 stage parallel

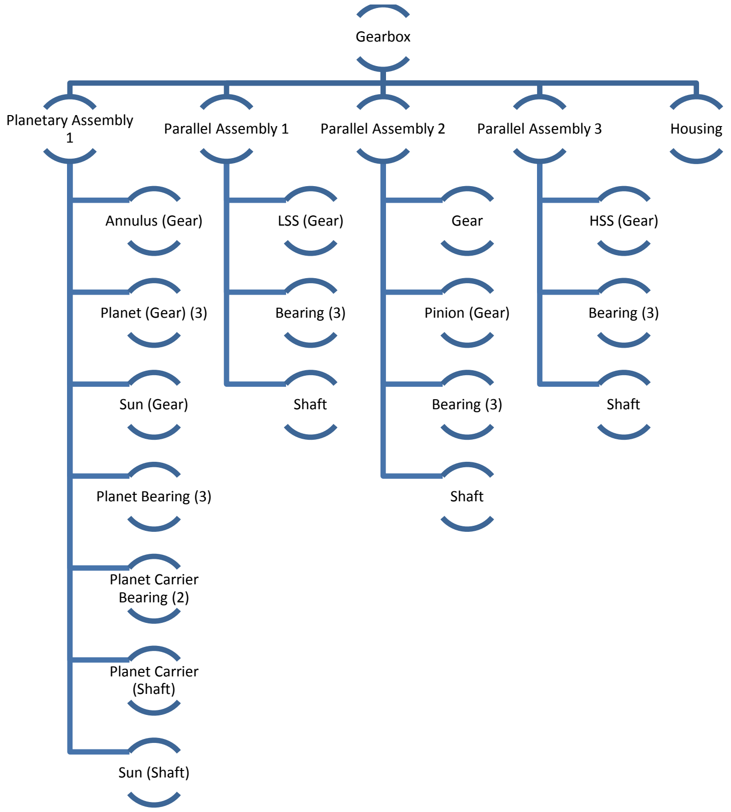


Figure 8-17 Gearbox 2 BoM and hierarchal structure of 1 stage planetary and 2 stage parallel

8.4.5.2 Process Model (Example C)

The process model for Example C expands upon that of Example B, highlighting the specific activities required for particular components. This requires parallel gateways to split the process for specific components, as shown in Figure 8-19. Further detail can be found within the sub processes for housing, bearing, gear and shaft rework. The gear rework sub process is shown in Figure 8-20 and highlights the different actions that can be taken after inspection. An exclusive gateway is required to split the different paths which can be taken to achieve component remanufacture. Probabilities of each path are determined using the case based reasoning gateway algorithm, which identifies similar cases and the paths which they followed within the process.

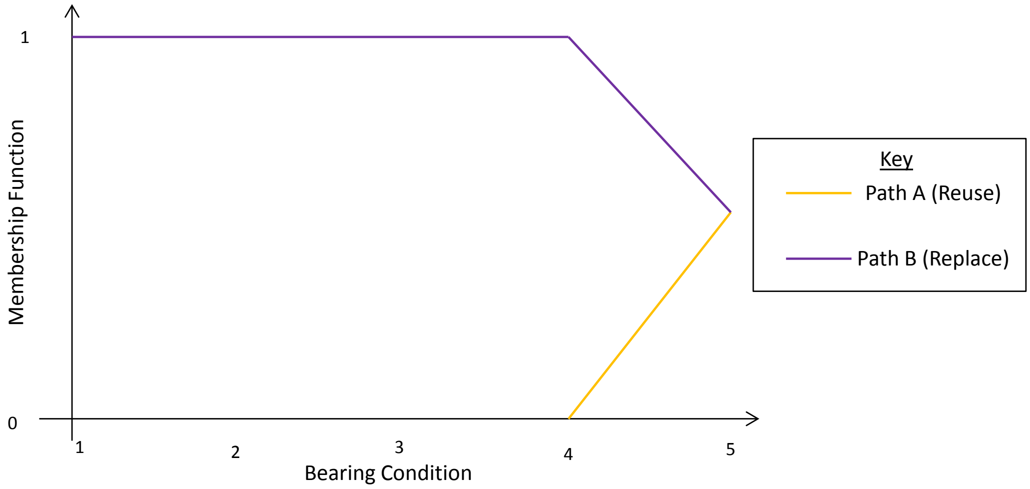


Figure 8-18 Membership function for the bearing rework gateway

As with example B, key attributes, weightings and matching types are input by the user into the process model for each activity and additionally gateways with multiple outputs, in the same manner as Table 8-9.

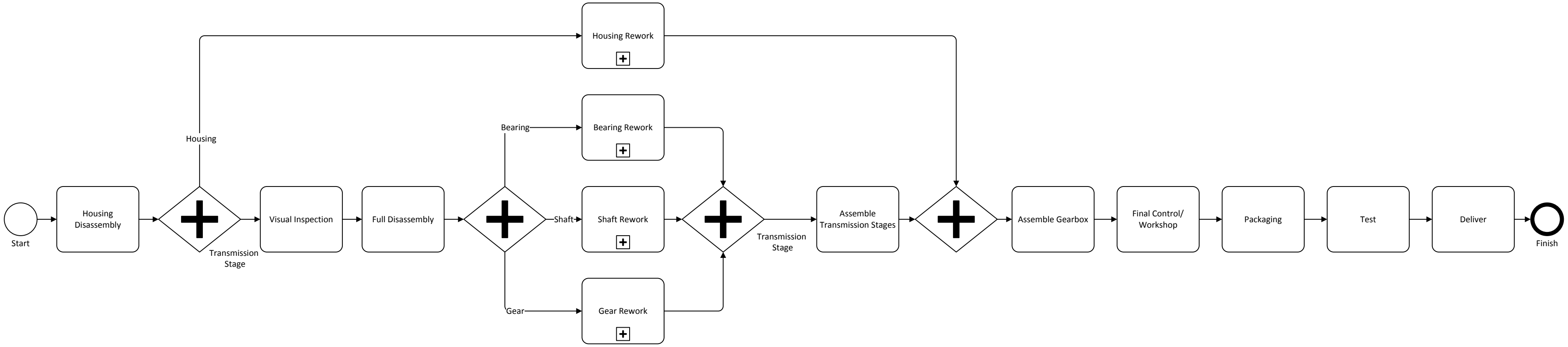


Figure 8-19 The process model for Example C

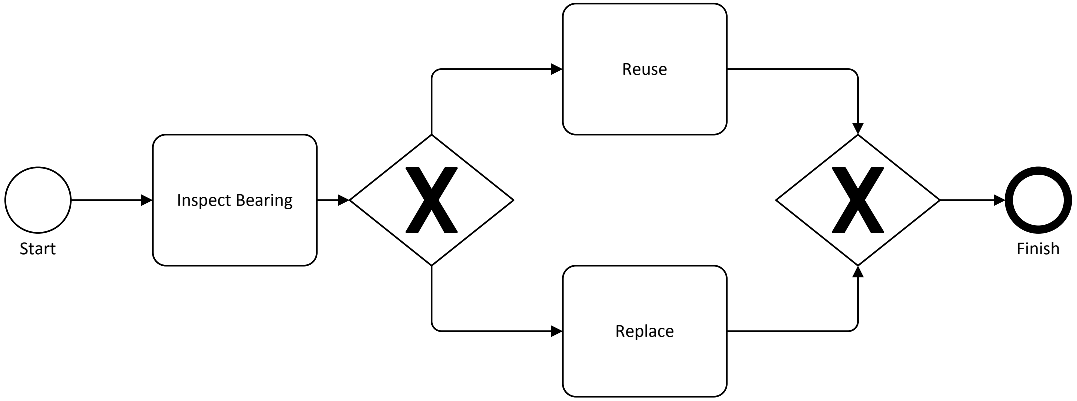


Figure 8-20 Expanded sub process of the bearing rework process

8.4.5.3 Activity Estimation Costs (Example C)

Activity estimates are used for certain bearing models, with information displayed within Table 8-12. This information has been generated for the purpose of this example but represents costs which may be found within an Enterprise Resource Planning (ERP) system.

Table 8-12 Activity cost estimates

ID	Manufacturer	Model	Rolling type	Inner Diameter (mm)	Bearing Replacement (£)
1	Manufacturer_A	X1	Cylindrical Roller	300	400
2	Manufacturer_A	X2	Cylindrical Roller	340	432
3	Manufacturer_A	X3	Cylindrical Roller	360	519
4	Manufacturer_A	X4	Cylindrical Roller	420	501
5	Manufacturer_A	X5	Cylindrical Roller	500	650

8.4.5.4 Historical Job Records (Example C)

Historical job records are used to estimate costs for the majority of activities within the remanufacturing process. The costs of previous bearing replacements are displayed in Table 8-13. Other examples of historical job records can be found within Appendix A. Costs for Manufacturer_A are generally lower than the others. This is due to the remanufacturing businesses being a subsiduray of Manufacturer_A, thus bearing prices are less.

Table 8-13 Historical job bearing records

Case ID	Manufacturer	Model	Rolling type	Inner Diameter (mm)	Cost (£)
Bearing_1	Manufacturer_A	X4	Cylindrical Roller	420	501
Bearing_2	Manufacturer_A	X3	Cylindrical Roller	360	519
Bearing_3	Manufacturer_A	X8	Cylindrical Roller	500	545
Bearing_4	Manufacturer_B	W2	Cylindrical Roller	450	1111
Bearing_5	Manufacturer_D	Z3	Ball Bearing	525	1637
Bearing_6	Manufacturer_D	Z7	Cylindrical Roller	600	2815
Bearing_7	Manufacturer_B	W1	Cylindrical Roller	350	1365
Bearing_8	Manufacturer_B	W1	Cylindrical Roller	350	1365
Bearing_9	Manufacturer_C	Y2	Cylindrical Roller	425	1428
Bearing_10	Manufacturer_C	Y17	Ball Bearing	380	1316
Bearing_11	Manufacturer_A	X11	Cylindrical Roller	785	1054
Bearing_12	Manufacturer_D	Z4	Cylindrical Roller	900	3992

8.4.5.5 Cost and uncertainty Calculation (Example C)

Cost estimation was then conducted by the tool. An overview of the total process results are shown in Table 8-14, whilst activity costs for bearing replacement within Gearbox 1 are displayed within Table 8-15.

Comparing the results of gearboxes 1 and 2, it can be seen that the total number of sub process required by each differs. This is due to the variation in product structure, demonstrating the tools capability of satisfying Requirement 3.1.2.

Table 8-14 Overview of the results for both gearboxes within Example C

	Gearbox 1	Gearbox 2
Total Cost (£)	56817	47529
Number of housing rework sub processes	1	1
Number of gear rework sub processes	13	9
Number of bearing rework sub processes	17	14
Number of shaft rework sub processes	6	5

Estimates of bearing replacements costs, displayed within Table 8-15, demonstrate the ability of the tool to use different cost information sources. If activity cost estimates are available (see Table 8-12) then they are used, if not historical job records are used to determine a cost through the CBR algorithm.

Table 8-15 Cost estimates for the bearing replacement activity within Gearbox 1

Parent Assembly	**Manufacturer**	**Model**	**Rolling type**	**Inner Diameter (mm)**	**10th Percentile (£)**	**Mean (£)**	**90th Percentile (£)**	**Estimate Source**
Planetary Assembly 1	Manufacturer_A	X5	Cylindrical Roller	500	650	650	650	Activity estimate
Planetary Assembly 1	Manufacturer_A	X10	Cylindrical Roller	550	212.9	1132.8	2110.7	Historical job records
Planetary Assembly 1	Manufacturer_A	X2	Cylindrical Roller	340	432	432	432	Activity estimate
Planetary Assembly 1	Manufacturer_A	X3	Cylindrical Roller	360	519	519	519	Historical job records
Planetary Assembly 1	Manufacturer_B	W1	Cylindrical Roller	350	608.7	1090.7	1617.9	Historical job records
Planetary Assembly 1	Manufacturer_A	*Unknown*	*Unknown*	800	0	1514.3	3174.6	Historical job records
Planetary Assembly 2	*Unknown*	*Unknown*	*Unknown*	*Unknown*	171.9	1440.6	2774.6	Historical job records
Planetary Assembly 2	Manufacturer_B	*Unknown*	*Unknown*	440	511.3	1136.9	1818.2	Historical job records
Planetary Assembly 2	Manufacturer_C	*Unknown*	*Unknown*	750	344.6	1754.3	3254.9	Historical job records
Planetary Assembly 2	Manufacturer_C	*Unknown*	*Unknown*	*Unknown*	214.6	1430.9	2716.5	Historical job records
Planetary Assembly 2	Manufacturer_A	*Unknown*	*Unknown*	*Unknown*	86.7	1330.5	2626.5	Historical job records
Parallel Assembly 1	Manufacturer_D	*Unknown*	*Unknown*	*Unknown*	203.9	1586.1	3041.7	Historical job records
Parallel Assembly 1	*Unknown*	*Unknown*	*Unknown*	430	243.1	1252.7	2327.0	Historical job records
Parallel Assembly 1	*Unknown*	*Unknown*	*Unknown*	540	247.1	1364.5	2551.3	Historical job records
Parallel Assembly 2	*Unknown*	*Unknown*	*Unknown*	*Unknown*	171.9	1440.6	2774.6	Historical job records
Parallel Assembly 2	*Unknown*	*Unknown*	*Unknown*	600	257.0	1422.2	2659.8	Historical job records
Parallel Assembly 2	*Unknown*	*Unknown*	*Unknown*	600	257.0	1422.2	2659.8	Historical job records

8.5 Discussion

8.5.1 Requirements

Two case studies consisting of three examples have been presented to demonstrate the functionality of the cost estimation tool. This section discusses how the functional requirements, listed in Table 8-16 have been demonstrated within the validation.

Requirement 1 relates to the ability of the tool to estimate the economic cost. The tool has accomplished this requirement through an analytical, activity based estimation approach. Using the process and product models, a set of activities required to remanufacture a product can be derived through the logic embedded within the tool. Summation of these activities then enables a total process cost to be estimated. This functionality has been demonstrated for all of the examples shown in this chapter through the estimation of cost for each.

Requirement 2 relates to the ability of the tool to estimate the economic cost and risk when uncertainties are present. This requirement has been subdivided into specific areas according to where uncertainties can occur, and are assessed individually. These are the Product Design (2.1), Product condition (2.2) and remanufacturing process (2.3). Requirement 2.1 relates to the assessment of risk due to uncertainty about a product’s design. This has been further split into the attribute information (2.1.1) and structural layout (2.1.2).

Requirement 2.1.1 is achieved by the tool through the Case Based Reasoning algorithm (CBR), discussed in section 6.2.1.2.2. When information regarding the key attributes is not present within the target estimation case a default value of 1 is given for the similarity of all of the previous records for that attribute, thereby nullifying its effect and relying upon the other attributes to determine appropriate costing. When no information is given other than the product type, which is the minimum information requirement, then the similarity score of all the cases are treated as equal. Cost results are then obtained through determining the weighted mean and standard deviation of the data set, and displayed using the normal distribution of these results. This process is best demonstrated within Example B, where four descriptions of the same gearbox are shown, each with a differing level of uncertainty. It can be seen that as the uncertainty increases in the product model, so too does risk in the estimate, shown through an increase in the range between the 10th and 90th percentiles in Table 8-11. Whilst the reduction in risk within the estimate is relatively small this can be explained due to a small data set used and the relatively high amount of noise found within it. Future work could investigate the performance of the CBR estimates relative to data set size and strength of cost relationships.

Table 8-16 Functional requirements list with the example demonstration link

Id	Requirement Description	Functionality demonstrated in example;		
		A	B	C
1.	**Cost Calculation** - The system shall estimate the economic cost of remanufacturing a particular product based upon the resource requirements under the following conditions; • Remanufacturing is treated as a single job lot (i.e. a lot size a 1). • The remanufacturing process begins as the product arrives at the factory and finishes upon its departure, i.e. logistical costs are not considered • The cost of storage is not considered within the estimate	✓	✓	✓
2.	**Risk and Uncertainty** - The system shall estimate the economic risk of remanufacturing a particular product due to the following uncertainties;			
2.1.	**Product Design** – The system shall allow calculation of cost when uncertainties regarding the product design are present. The uncertainties refer to the following specific product design aspects;			
2.1.1.	*Key Attributes* – When key attribute information, such as product weight, is unknown.		✓	✓
2.1.2.	*Structural Layout (BoM)* – When the number and type of components making up the product are unknown.		✓	
2.2.	**Product Condition** – The system shall allow calculation of cost when uncertainties regarding the product condition are present. The uncertainties refer to the following specific types;			
2.2.1.	*Unknown Condition* – When no information exists regarding the information of the product condition.		✓	✓
2.2.2.	*Ambiguous condition* - When information related to the product condition does not always correlate to an exact process outcome.	✓		✓
2.3.	**Process –** The system shall account for uncertainties related to the remanufacturing process within the cost estimation for the following factors;			
2.3.1.	*Inherent process variations* – Where inherent variations may occur from one process to another when all other given factors are equal, such as disassembly time.		✓	✓
2.3.2.	*Process knowledge uncertainties* – When information about specific remanufacturing activities is unknown due to a lack of experience.		✓	✓
3.	**Generic Functionality** – The system shall be robust to ensure that a generic remanufacturer can use the tool specifically for their application. In order to comply with this requirement, the following specific sub elements have been outlined;			
3.1.	**Product Design** – The system shall provide a generic product model, in which specific products can be described. Explicitly it is comprised of the following requirements;			
3.1.1.	*Product Types* – The product model shall allow for multiple types of product and component to be described. It should allow for specific attributes which may be unique to particular products to be described.	✓		✓
3.1.2.	*Variations within product types* – The product model shall also allow variations between products types to be described, such as the number and type of components that it may contain.			✓
3.2.	**Process Design** – The system shall provide a generic process information model, in which specific remanufacturing process can be described. The process shall allow the generic remanufacturing activities to be described, as shown in section 2.3.2.1. The process should allow the possible permutations that may occur to be described.	✓		✓
3.3.	**Cost information –** The system shall enable cost information from multiple sources to be used.			✓

The second element of uncertainty within the product design is within its structure (2.1.2), such as an unknown number of components. The method by which this is addressed is through using a less detailed product structure. This is demonstrated by the comparison of Examples B and C. Both of these examples represent the remanufacture of a gearbox, however within Example B information relating to the sub components and assemblies are not given. Instead a simplified process model is used where the detailed activities related to each subcomponent are not present. Instead the historical cost information is amalgamated within the database, giving a total cost for each of the three highlighted activities. Whilst this method fulfils the objective, it requires the user to specify a simpler process model. Future development of this function could automate this process, allowing for simpler use.

The uncertainty about the product condition can be expressed in two ways. The first relates to an unknown condition (2.2.1), whilst the second relates to ambiguity regarding the effect of a condition value (2.2.2).

Requirement 2.2.1 is addressed within the tool in much the same way as 1.1.2, which is through the CBR algorithm. Again Example B demonstrates the effect of missing condition information upon the cost estimate within Table 8-8. Product condition is also used to dictate the outcome path of an exclusive gateway. When unknown, conditions are treated as an evenly distributed random condition value. This is demonstrated within example A and shown in Table 8-7, highlighting the increased level of uncertainty.

Requirement 2.2.2 concerns the ambiguity of a product’s condition in relation to the process outcome. The tool fulfils this requirement by representing ambiguity through the use of fuzzy sets to represent the outcomes at exclusive gateways. This functionality is demonstrated within Examples A and C, and shown in Figure 8-8 and Figure 8-18 respectively. The fuzzy set membership enables multiple potential outcomes from a single condition value, at varying probabilities. A limitation of the current implementation of this function within the tool is that the memberships require manual derivation. An improvement to this functionality would be to automate the membership set distributions using historical data sets. This would allow the system to update as the remanufacturer’s knowledge base increased.

The final area of uncertainty covered by this tool relates to that found within the remanufacturing process (2.3). This has been split into inherent process variations (2.3.1) and process knowledge uncertainties (2.3.2).

Requirement 2.3.1 relates to the inherent variations which can occur within resource requirements of process activities, such as the time to disassemble a product. Within the tool, this is accounted for by the case based reasoning algorithm, in particular the use of a probability distribution to describe the historical data set, detailed in section 6.2.1.2.2. This functionality can be seen within examples B and C where individual activity estimates 10th and 90th percentile costs differ even when product descriptions contain no uncertainty and historical cost data exists.

The process knowledge uncertainties (2.3.2) relate to information uncertainty about the resource requirements of remanufacturing activities due to insufficient experience with a particular product. To deal with this uncertainty the CBR algorithm is again used. Using intuitive experts' opinion, key attributes related to a product or component are identified which influence the resource, and ultimately the cost, requirements of an activity. Then based upon these attributes, the CBR algorithm will identify similar examples of previous remanufacturing cases from historical job records and use them to estimate the activity cost. This function is primarily demonstrated within Example B where the type of gearbox which is being estimated has not been remanufactured before.

Requirement 3 concerns upon the generic functionality of the tool, referring to its ability to be used by different remanufacturing businesses. It has been split into three sections relating to the generic representation of the product design (3.1), process design (3.2) and cost information (3.3).

Requirement 3.1 refers to the ability of the tool to estimate remanufacturing costs for different products. This has been split into two requirements. The first ensures different product and components types can be detailed (3.1.1), whilst the second allows structural variations to occur within the same product type (3.1.2). Both of these objectives have been achieved through the robust design of the product model.

The allowance of different product types to be described using the same product model (3.1.1) has been achieved through the design of the class structure within the product model. Common attributes found amongst all products are grouped within the Design Info class, such as the manufacturer, whilst custom properties are stored within the Property class. This functionality has been demonstrated within Examples A and C through the representation of multiple different product types. Within Example A, product information regarding an engine containing subcomponents of cylinder head, cylinder block, piston, connecting rod, crankshaft, flywheel and turbo charger have been modelled, whilst Example C contains a wind turbine gearbox with sub components of planetary, spur, annulus gears, bearings, shafts and housing. Unique design properties of the products or components are held as an object within the property class, such as the swept volume on an engine shown in Figure 8-4. The influence of these properties are felt during activity cost estimation through the CBR algorithm. Key properties requirements are outlined within the process model within the CBR class, which the tool then uses to compare product model values with historical cost records.

Variations within product types (3.1.2), such as different gearbox configurations, have again been achieved through the design of the product model. The component instance class within the product model, allows parent and child relationships to be established between components. The number of sub components is not unique to a particular product type, therefore variations within the product model can be created. The cost estimation method then determines the appropriate number of activities to use based upon the number of components within the product model, described in section 6.2.1.1.1. This functionality is demonstrated within Example C where two gearboxes were modelled containing different numbers of planetary and spur stages. Each product is then estimated using the same process model resulting in a unique number of activity requirements related to its number and type of components. An aspect within the product model which could be improved is the addition of the type of connection linking components, such as a screw, snap fit or adhesive bond. This information would be useful in estimating disassembly and assembly costs, however it currently has not been considered within the cost tool due to resource and time constraints.

Requirement 3.2 requests a generic method of expressing the remanufacturing process so that the particular details of a specific business process can be expressed in a repeatable manner. This has been achieved within the tool through the design of the process model. The process model allows a variable workflow to be represented through a series of generic objects labelled as process blocks, described in section 6.3.1.2. These process blocks enable the workflow, remanufacturing activities and decisions to be represented. These can then be arranged to represent a remanufacturing process. This is demonstrated within examples A and C, with detailed remanufacturing processes specific to each business represented.

The final requirement relates to the method in which activity costs are derived (3.3). It is understood that activity estimation sources may vary between, or even within a business and can be derived from intuitive, analogical and parametric sources, highlighted in section 5.3.2.1. To represent this cost information within the tool, specific classes have been designed within the product model. Two types of cost information have been represented within the tool, intuitive estimations and historical job records, which are recorded within the Activity and Activity_Estimate_Set classes of the product model, described in section 7.4.5. Simple heuristic rules enable the tool to determine which type of cost information to use within the estimation. There applications have been demonstrated within Examples A and B whilst Example C demonstrates the ability to use either technique. Future work should be conducted to further establish how businesses record historical product remanufacturing information, to ensure alternative methods are available to derive cost should they be required.

8.5.2 Future Work

Whilst all the requirements outlined within the specification have been satisfied, further work should be considered to validate the performance of the tool, relative to the accuracy of the cost estimation.

An estimate has been provided for all of the activities and processes requested. However, the accuracy of the estimates and the quality of results they provide to the end user at present are questionable. For the estimates produced within Example B, the range in risk between the gearboxes, shown in Table 8-11, is less than expected. Whilst a high level of risk is determined for the high uncertainty case (Gearbox_4), a lower but still relatively high risk value is also calculated for the lowest uncertainty case (Gearbox_1). Similar finding can be found in example C, displayed within Table 8-15. There are several possible reasons for this including insufficient number of historical cases within the data set, high variation in historical costs, poor selection of weighting values and incorrect distribution type within the case based reason algorithm.

Future work should focus upon improving the accuracy of the tool, through optimisation of the algorithm design and selection of appropriate parameters. This could be implemented through a thorough sensitivity analysis of the parameters, using controlled data generated for the purpose of validation. Additionally testing of the tool in an industrial setting and comparing predicted cost to actual results would allow for through validation.

8.6 Chapter 8 Summary

Within this chapter the validation for the developed software tool was presented through the use of two business case studies. Examples were then presented to demonstrate the functionality of the cost estimation tool relative the requirements specification outlined in Chapter 4. A discussion was then conducted to justify how each of the specification requirements had been achieved and where future improvements could be made.

Within the discussion it was determined that each of the specification requirements had been satisfied. Cost calculation (Requirement 1) was achieved by the analytical activity cost method described with Chapter 6. Uncertainty requirements (2) were fulfilled through the CBR algorithm, fuzzy sets and Monte Carlo simulation. Generic functionality (Requirement 3) was achieved through the design of the product and process models which have enabled the key generic features to be represented in a manner where they can be further specialised to express specific details about each case.

It was also highlighted that a number of areas could be improved. Future work to develop the tool should focus upon enhancing the performance and usability. Optimisation to improve the accuracy of the cost estimates is an area of particular attention. Current estimates produce higher than expected risk values, devaluing estimates with a relatively low level of uncertainty within the product model. A number of reasons are identified for this within the future work section (8.5.2).

9 Conclusion

9.1 Summary of Thesis and Research Conclusions

Remanufacturing in the correct circumstances can produce high quality products at reduced cost and environmental impact relative to traditional manufacturing. However, remanufacturing does not necessarily provide these benefits and is affected by a number of factors such as the market demand, product design, product condition and business capabilities. Therefore careful assessment should be conducted before beginning a remanufacturing endeavour. This thesis has attempted to address the issue of assessing the feasibility of a product for remanufacture. The aim proposed at the beginning of this thesis was;

How can the assessment of product feasibility for remanufacture be better supported?

To achieve the overall aim four objectives were outlined. A summary of how each objective was achieved, as well as the main conclusions are explained below:

1. *Identify the requirements and factors used in assessing product feasibility for remanufacture;*
   Summary - Within Chapter 2 a literature review supplemented with findings from industrial interviews was conducted to identify the requirements and factors used to assess product feasibility for remanufacture. Requirements for remanufacturing could be grouped in accordance to the triple bottom line of sustainability, economic, environmental and social, whilst the factors affecting the decision fell into groups related to the market, the product design, the product condition and the business capabilities.
   Conclusions - The influence of each of these factors varied depending upon the stage of the business in which the decision was being conducted, with strategic, tactical and operations decision stages being identified. An additional challenge which remanufacturers deal with is the high level of uncertainty regarding the available information to make their decision.
2. *Identify and evaluate methods and tools which help assess remanufacturing feasibility and identify gaps in the research;*
   Summary – Within Chapter 3 the methods and tools developed to assess remanufacturing feasibility were identified and evaluated using a systematic review process. In total 41 tools were found to be relevant to the topic and were reviewed.
   Conclusions -The major finding from this review established a need for more tools to consider and evaluate the uncertainty associated with a decision and measure the impact upon the evaluation criteria such as economic cost, time, quality and environmental impact.
3. *Design and implement a novel tool to support the assessment of remanufacturing feasibility;*

Summary - Based upon the findings of objectives 1 and 2, it was determined in Chapter 4 that a tool should be designed and implemented to estimate the economic cost of remanufacturing a product at the tactical and operational stages in the presence of uncertain information. A requirements specification was also presented within this chapter to act as a design brief. A review of cost estimation techniques and methods of assessing uncertainty was conducted within Chapter 5. The final design of the tool is detailed within Chapter 6, whilst the implementation and detailed design of the software is described in Chapter 7.

Conclusions - This review found that an analytical technique would be most suited the estimation problem, whilst stochastic modelling was deemed a suitable method for resolving uncertainties. An analytic costing method was used based upon the activities required to conduct remanufacture. Uncertainties were dealt with using a combination of stochastic modelling using Monte Carlo simulation to resolve process activity uncertainties, whilst the addition of case based reasoning was employed to resolve individual activity cost estimation uncertainties. Generic models for representing the products and remanufacturing process were also designed/developed enabling the tool to be robust in enabling an array of specific products and processes to be estimated. The tool was implemented within an object oriented structure using the Visual Basic programming language and deployed as a RESTful web service, described within Chapter 7.

4. *Test and evaluate the proposed support tool;*

   Summary - The tool has been tested using two case studies, within Chapter 8. Evaluation was conducted by comparing the functionality against the set of specification requirements, and outlined in Chapter 4. Functions were split into three key areas; the ability to produce a cost estimate, the uncertainty which the estimate deals with, the robustness of the tool within different remanufacturing environments.

   Conclusions - Each area was successfully addressed, suggesting that the tool is suitable for estimating the economic cost and impact of uncertainty for a range of products undergoing remanufacturing processes.

9.2 Research Contributions

The work conducted within this project and reported in this thesis has produced one primary and two secondary research contributions. The major research contribution from this research project is;

- The design of a novel tool to estimate the economic cost of remanufacturing a product with uncertain information

Whilst several other tools have been developed to estimate the cost of remanufacture, this is the first to do so when information required for the estimate is uncertain. The tool can be useful for decision makers assessing the remanufacturability of a product in the following ways;

a) Allows the user to assess the risk associated within the estimate, thus adding an extra dimension to the economic assessment of remanufacture.
b) Utilises historical information generated by a business to reduce the uncertainty within an estimate.
c) Assesses uncertainty of both product and process, which is the first time has been done within the remanufacturing domain.

In addition, two secondary research contributions have been made, these are;

- A detailed review of the tools and techniques developed to assist the assessment of remanufacturing feasibility
- The depiction of two detailed case study examples, highlighting the uncertainty within the assessment of product feasibility for remanufacture, which have been used to test and validate the tool.

Prior to this research there had been no thorough review of the tools developed for this purpose, even though a substantial number of tools had been developed. An understanding of the requirements for the assessment of remanufacturing feasibility was developed within Chapter 2, which was then used to review the tools found within Chapter 3. The implications of this research contribution should allow researchers a clearer set of requirements when developing future tools for this purpose. This research has been written as a journal paper and published within the Journal of Cleaner Production (Goodall et al.:2014).

The final research contribution comes from the depiction of the detailed case studies used to validate and test the cost estimation tool. These case studies identify particular information uncertainties faced within the remanufacturing. At present no case study is detailed within literature with the focus of demonstrating where information uncertainties may lie, and the variations within the information requirements to describe products and processes. These case studies can therefore be useful to future researchers who wish to develop support tools for remanufacture.

9.3 Future Work

Future work has been split into two categories; the first explores future work related to the area of support tools to assess the feasibility of remanufacturing, whilst the second details further developments to be made to the cost estimation tool.

9.3.1 General tools for assessing remanufacturing feasibility

As identified within Chapter 4, there remain a number of research avenues to develop tools and methods that assist the assessment of remanufacturing feasibility. The implication of the time taken to remanufacture a product is rarely considered within the identified tools and would be useful to consider where remanufacturing of a product results in downtime for the customers' business.

A quantitative analysis, investigating the potential benefits of a tool, regarding proposed time and cost savings would be beneficial toward the adoption within industry. This analysis could be conducted using a mathematical model to provide ‘what if’ scenarios based upon savings from the proposed use of the tool.

9.3.2 Cost Estimation Tool Improvements

Although the software tool has been designed, implemented and tested as a fully functional prototype web based software program, further work will be required before the tool is ready to be used by industry. Three general areas have been outlined for further development;

- User Interfaces
- Optimisation of algorithm for performance and accuracy
- Further investigate into how remanufacturing businesses record cost information
- Implementation of data collection from distributed data sources

Improved user interfaces will be required to develop the cost estimation tool further. These are necessary to create the product and process models in a simpler manner, and also display the results effectively. A graphical method of creating a process model would be beneficial to the overall usability of the tool. At present the process models are created manually within a database, however this task is time consuming and prone to human error. It is envisaged that a graphical tool, similar to Microsoft Visio, could allow the process model to be graphically generated in a similar manner to those shown in Chapter 8, would simplify this procedure. The information contained within the models could be saved and transferred to the software tool through a common language such as XML.

So far the tool has been evaluated functionally, however, additional performance criteria should be investigated within future work. The performance criteria should relate to the accuracy of the cost estimate and the speed of execution to ensure it satisfies the user’s requirements. The accuracy of the estimate could be conducted by trialling the tool within the factory setting, predicting the cost prior to remanufacture, monitoring actual costs incurred, then comparing the results. Over a number of estimations, the distribution of estimates to real costs can be created to evaluate whether the accuracy of the tool is correct. Unfortunately this could not be conducted during this thesis due to the availability of industry data and resource constraints.

Currently two methods of recording cost information have been incorporated into the cost estimation tool, intuitive activity estimation and analogical historical job records. Further investigation should be conducted into how businesses record resource consumption and cost information to enable a more robust method of determining costs, resulting in the tool being useable within a wider range of remanufacturing businesses.

Finally further work is required to enable data to be obtained from distributed sources. The tool has been designed in a generic manner to represent data from a range of sources. Currently information resides within databases situated locally alongside the tool. Further work is required to develop and extend the existing set of web services to obtain information from external data sources, such as ERP and condition monitoring systems.

10 References

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Appendix A Case Study Data Inputs

This appendix contains the information used to create the product and process models as well cost information from activity estimates and historical job records for the validation case studies, shown in Chapter 8. Product structures and process workflows have been recreated from interviews and discussions with the industrial case studies, however detailed attribute and cost information has been generated from demonstrative purposes. The detailing of this information is to illustrate the types and quantity of information required for the cost estimation tool.

A.1 Case 1 Data Inputs

A.1.1 Product

The product which is described in Case 1 is an automotive engine, made up of eight subcomponent types shown in Figure A - 1 and is comprised of nineteen components identified within Table A - 1. As activity estimates are used and not the historical job records to determine activity costs, only the component type, design Id and condition attributes are required.

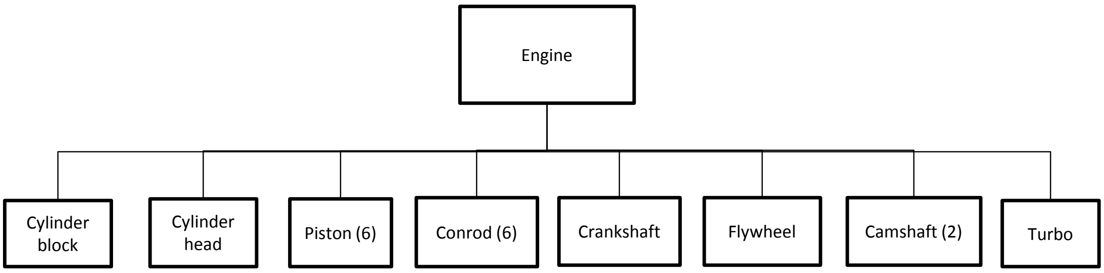


Figure A - 1 Product model BoM for the engine

Table A - 1 Attribute information for the product model

Component_ID	Parent	Type	Design_ID	Condition
Engine	N/A	Engine	DUC_Engine	55
Cylinder_Block	Engine	Cylinder Block	DUC_Cylinder_Block	73
Cylinder_Head	Engine	Cylinder Head	DUC_Cylinder_Head	56
Piston_1	Engine	Piston	DUC_Piston	80
Piston_2	Engine	Piston	DUC_Piston	46
Piston_3	Engine	Piston	DUC_Piston	45
Piston_4	Engine	Piston	DUC_Piston	82
Piston_5	Engine	Piston	DUC_Piston	70
Piston_6	Engine	Piston	DUC_Piston	51
Conrod_1	Engine	Conrod	DUC_Conrod	16
Conrod_2	Engine	Conrod	DUC_Conrod	56
Conrod_3	Engine	Conrod	DUC_Conrod	54
Conrod_4	Engine	Conrod	DUC_Conrod	53
Conrod_5	Engine	Conrod	DUC_Conrod	62
Conrod_6	Engine	Conrod	DUC_Conrod	21
Crankshaft	Engine	Crankshaft	DUC_Crankshaft	72
Flywheel	Engine	Flywheel	DUC_Flywheel	86
Camshaft_1	Engine	Camshaft	DUC_Camshaft	31
Camshaft_2	Engine	Camshaft	DUC_Camshaft	43
Turbo	Engine	Turbo	DUC_Turbo	50

A.1.2 Process

The process model consists of nine process workflows, including the top level process workflow, shown in Figure A - 2, and eight sub process shown in figures A-2 to A-10. Some activity names have been removed for confidentiality reasons.

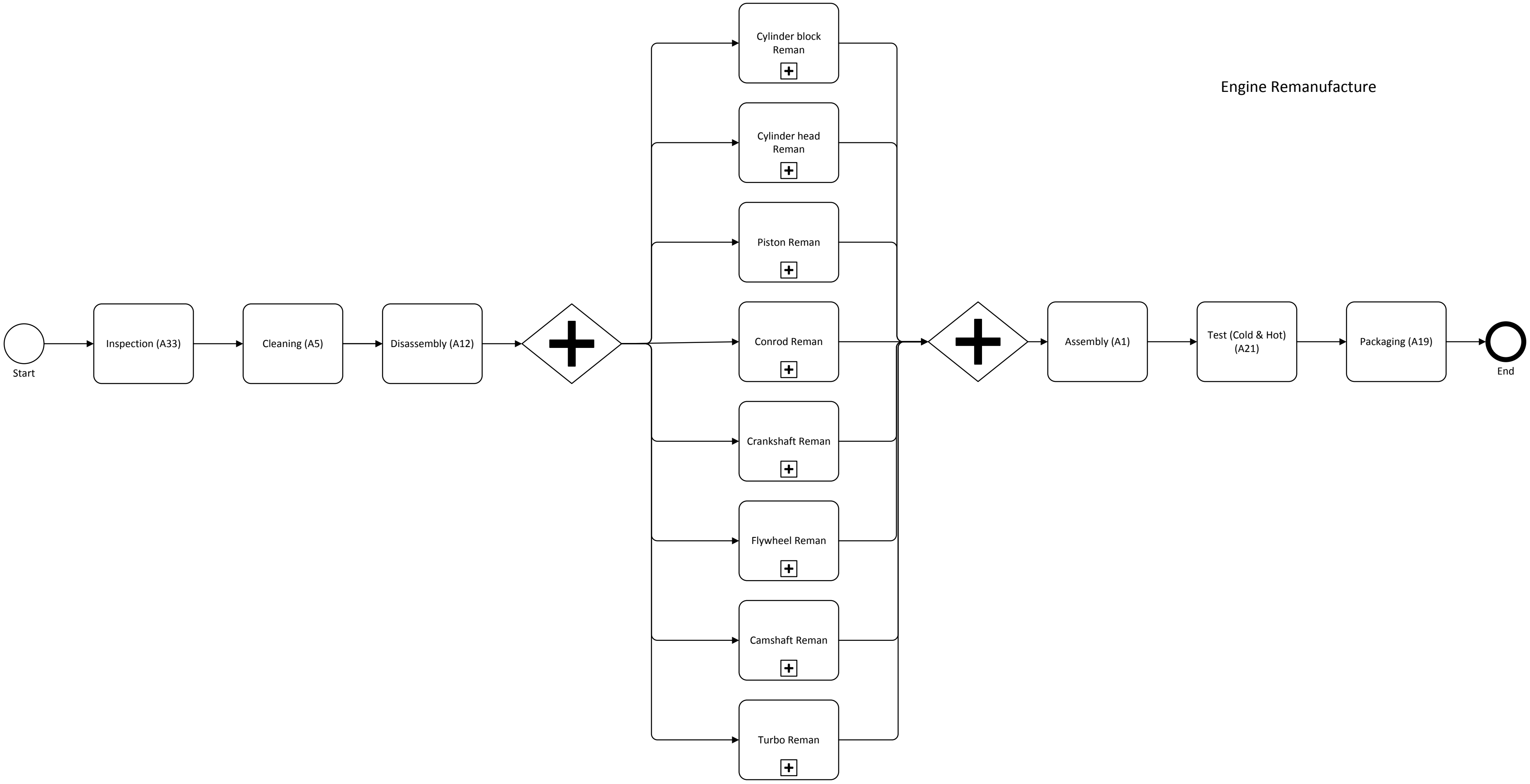
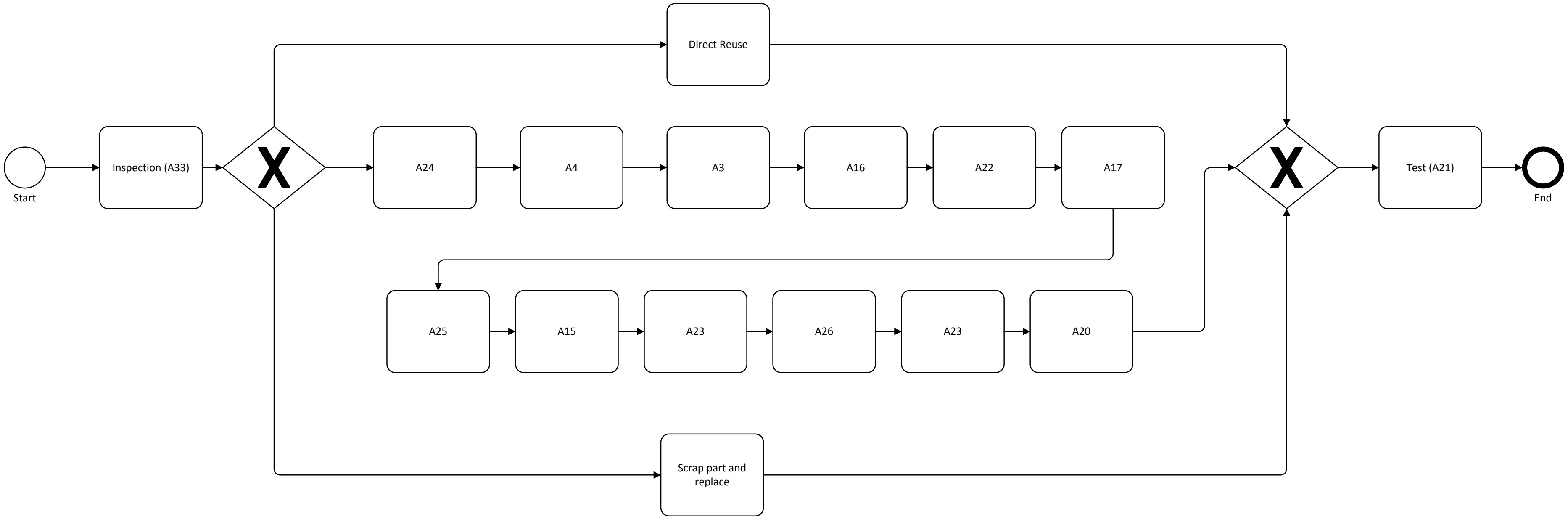


Figure A - 2 Top level engine remanufacturing process workflow



Cylinder Block Remanufacture

Figure A - 3 Cylinder block remanufacturing sub process workflow

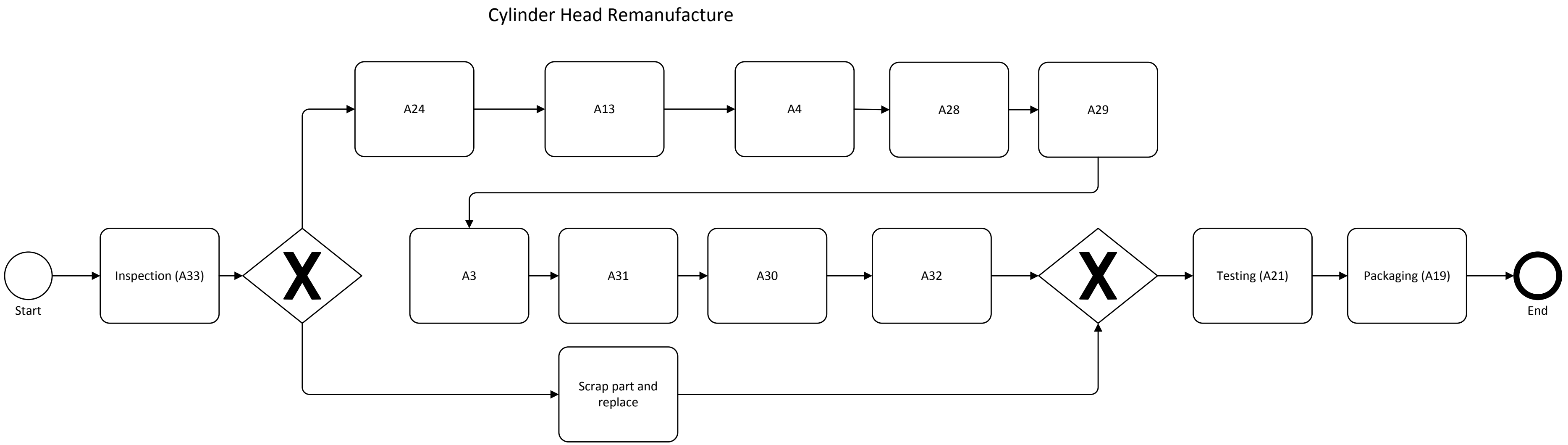


Figure A - 4 Cylinder head remanufacturing sub process workflow

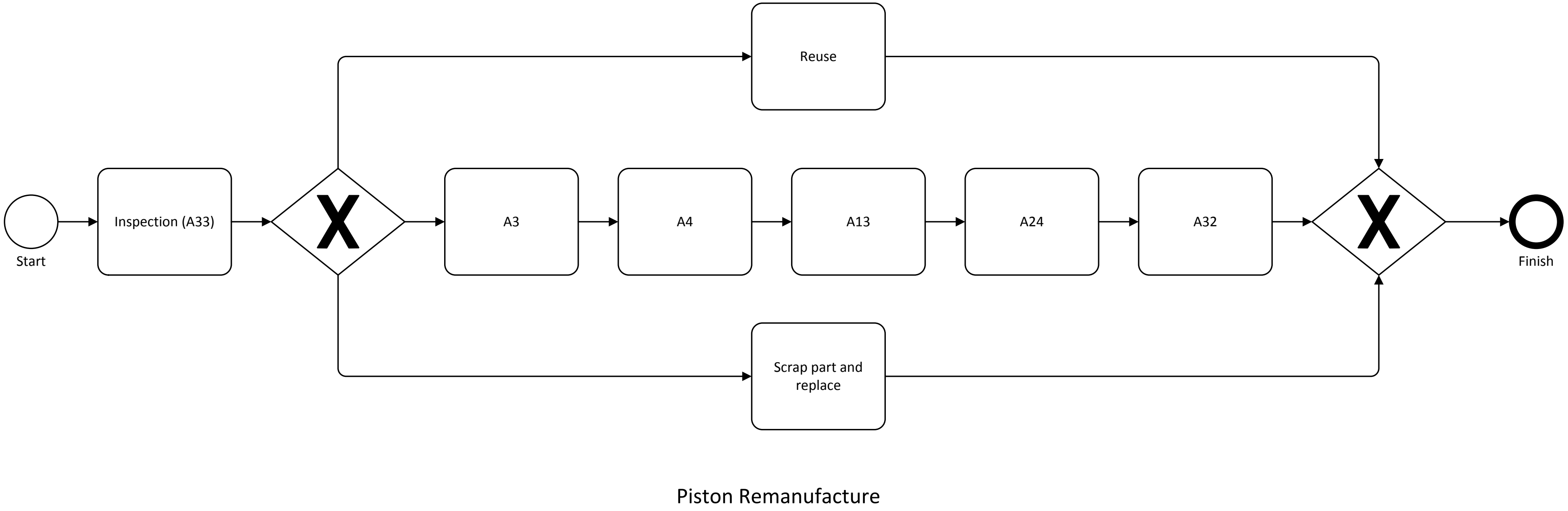


Figure A - 5 Piston remanufacturing sub process workflow

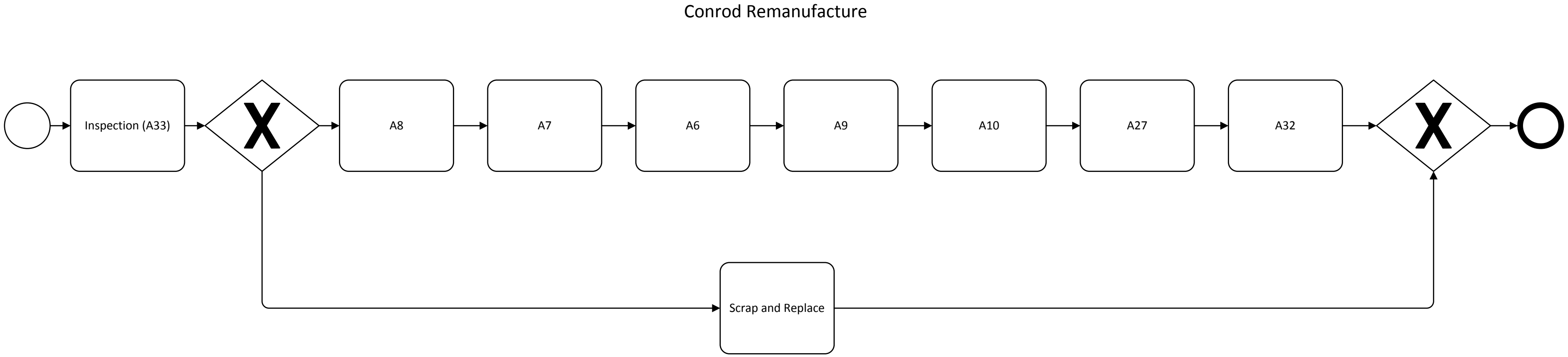


Figure A - 6 Connecting rod remanufacturing sub process workflow

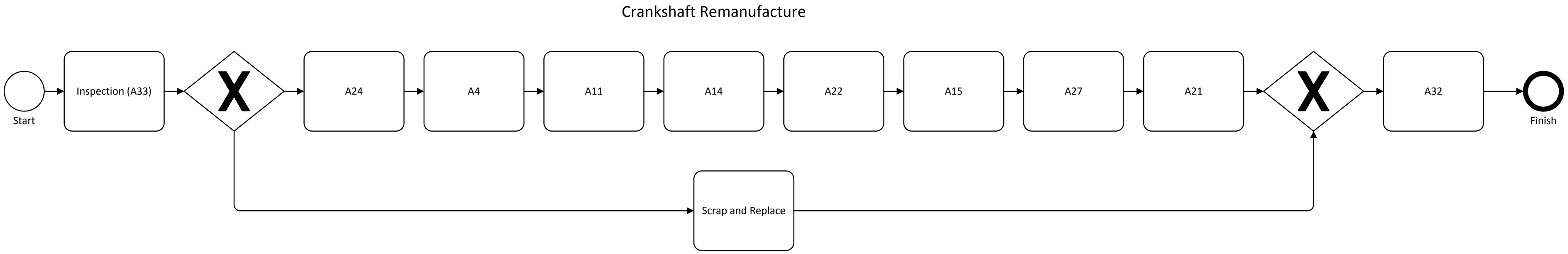


Figure A - 7 Crankshaft remanufacturing sub process workflow

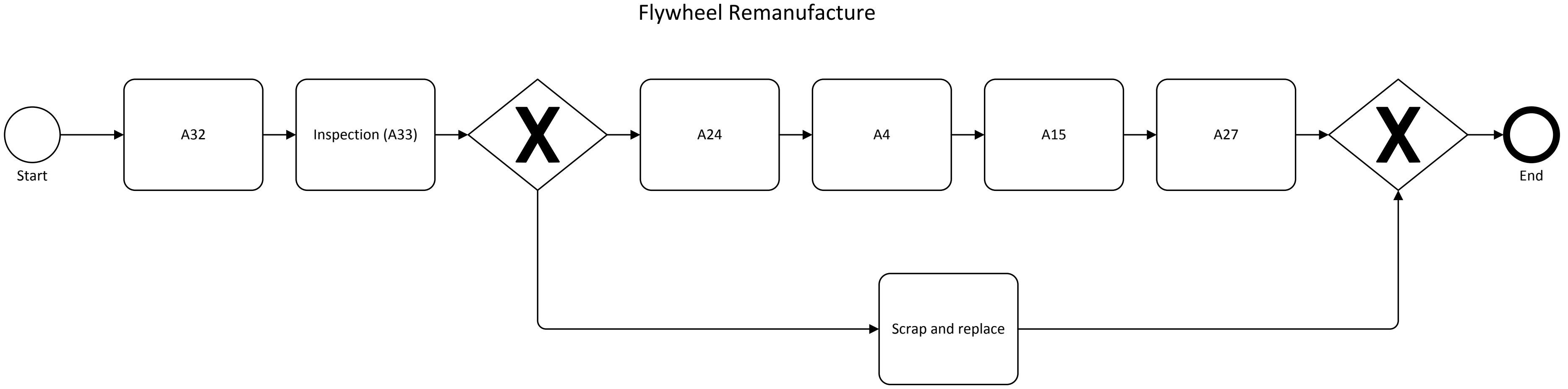


Figure A - 8 Flywheel remanufacturing sub process workflow

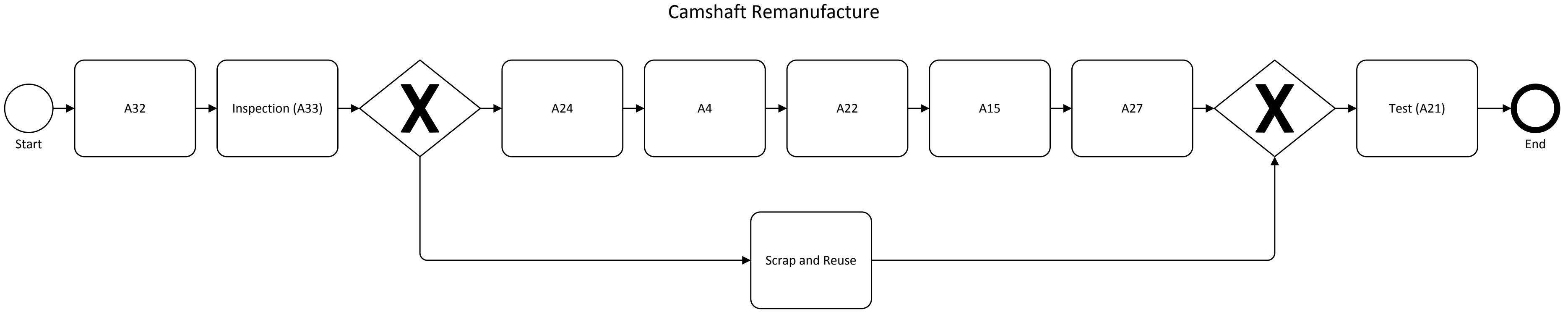


Figure A - 9 Camshaft remanufacturing sub process workflow

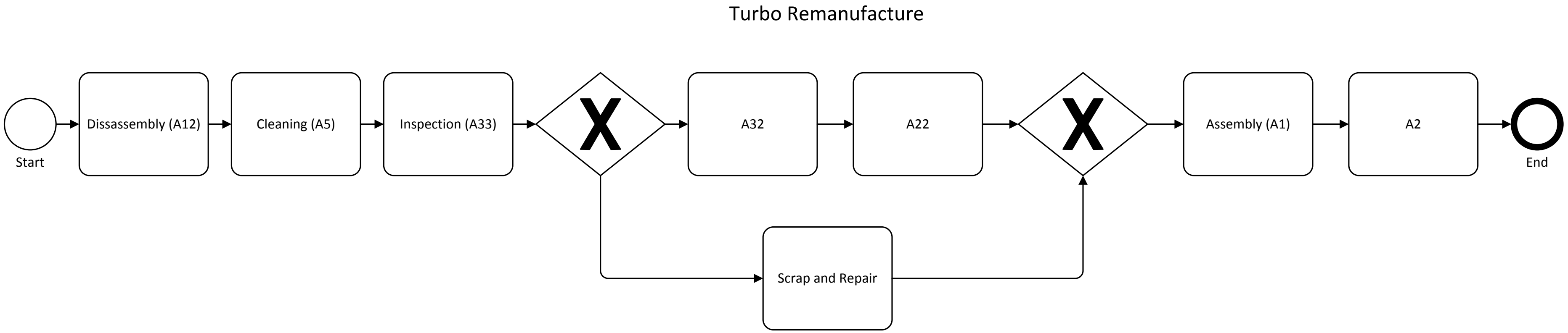


Figure A - 10 Turbocharger remanufacturing sub process workflow

A.1.3 Exclusive Gateway Fuzzy Sets

To describe the decision logic at the decision gateways fuzzy memberships are required. Two fuzzy sets have been used with the process. The first is for exclusive gateways with three outcome paths, whilst the second is for two outcome paths, shown in Figure A - 11 and Figure A - 12 respectively.

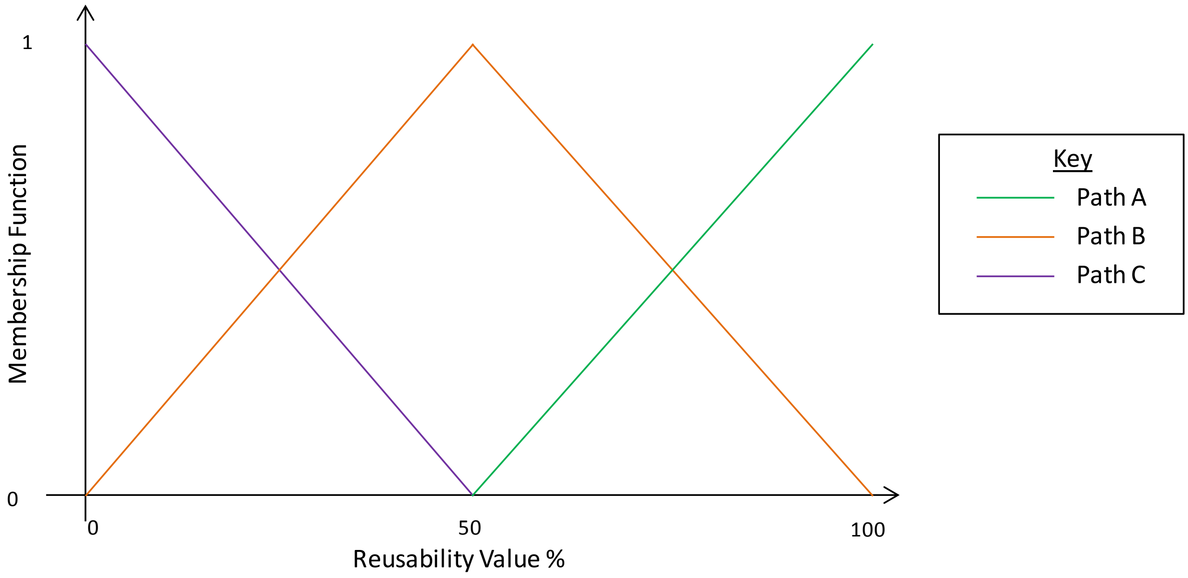


Figure A - 11 Fuzzy sets for three outgoing paths

Table A - 2 Information requirements to describe the fuzzy membership functions for the three going paths

Fuzzy membership attribute	**Outgoing Path**		
	A (Reuse)	**B (Rework)**	**C (Replace)**
Lower Min	50	0	0
Lower Max	100	50	0
Upper Max	100	50	0
Upper Min	100	100	50

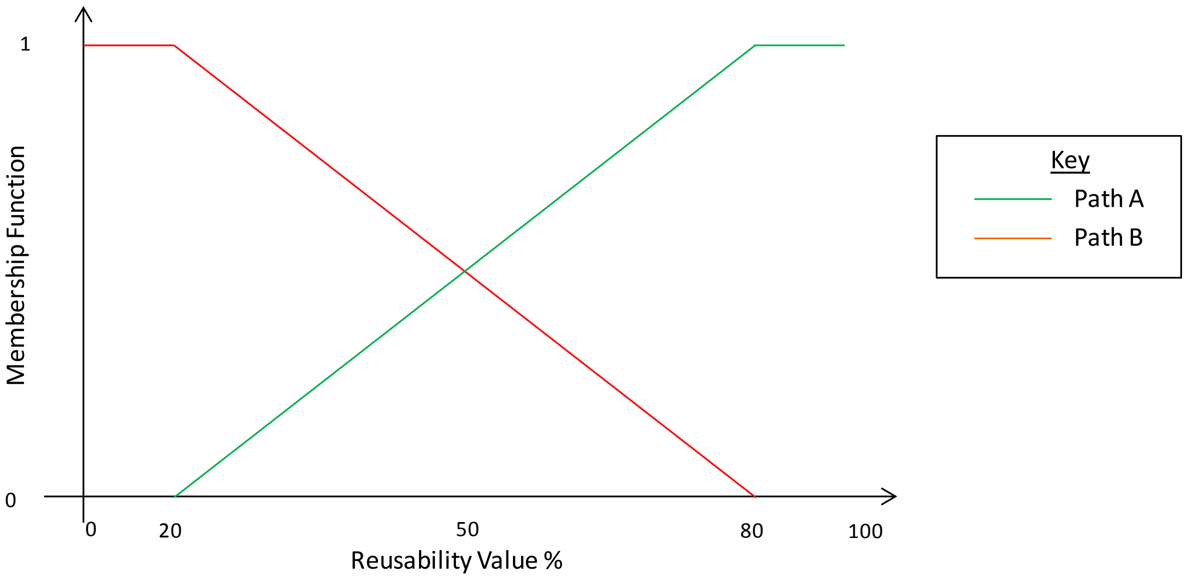


Figure A - 12 Fuzzy sets for two outgoing paths

Table A - 3 Information requirements to describe the fuzzy membership functions for the two going paths

Fuzzy membership attribute	**Outgoing Path**	
	A (Rework)	**B (Replace)**
Lower Min	20	0
Lower Max	80	0
Upper Max	100	20
Upper Min	100	80

A.1.4 Activity Costs

A cost estimate is derived for each activity based upon the estimated resource consumption. For each of the activities identified within the process workflows above, an estimate of the resource consumption is outlined within the tables A -4 to A – 12 below. Some activity names have been removed for confidentiality reasons.

Table A - 4 Activity costs for engine remanufacture

Activity	**Engine**		
	Labour (h)	**Machine (h)**	**Replacement**
A1 Assembly	1.03	0	0
A5 Cleaning	0	0.3	0
A12 Disassembly	1.8	0	0
A19 Packaging	0.3	0	0
A21 Test (Cold & Hot)	0	1.92	0
A33 Inspection	0.11	0	0

Table A - 5 Activity costs for Piston remanufacture

Activity	**Piston**		
	Labour (h)	**Machine (h)**	**Replacement**
A3	0	0.015	0
A4	0.018	0	0
A13	0	0.07	0
A24	0	0.023	0
A32	0	0.034	0
A33 Inspection	0.05	0	0
Reuse	0	0	0
Scrap Part & Replace	0	0	1

Table A - 6 Activity costs for cylinder block remanufacture

Activity	**Cylinder Block**		
	Labour (h)	**Machine (h)**	**Replacement**
A3	0	0.03	0
A4	0.02	0	0
A5	0.051	0	0
A15	0	0.045	0
A16	0.076	0.76	0
A17	0.08	0	0
A20	0.015	0	0
A21 Test	0.025	0	0
A22	0	0.23	0
A23	0.012	0	0
A24	0	0.03	0
A25	0	0.08	0
A26	0	0.07	0
A32	0.051	0	0
A33 Inspection	0.09	0	0
Reuse	0	0	0
Scrap Part & Replace	0	0	1

Table A - 7 Activity costs for cylinder head remanufacture

Activity	Cylinder Head		
	Labour (h)	**Machine (h)**	**Replacement**
A3	0	0.025	0
A4	0.018	0	0
A13	0	0.04	0
A18	0	0.047	0
A19 Packaging	0.02	0	0
A21 Test	0.025	0	0
A24	0	0.03	0
A28	0.005	0	0
A29	0.2	0	1
A30	0.15	0	0
A31	0.09	0	0
A32	0.047	0	0
A33 Inspection	0.09	0	0
Reuse	0	0	0
Scrap Part & Replace	0	0	1

Table A - 8 Activity costs for connecting rod remanufacture

Activity	Connecting Rod		
	Labour (h)	**Machine (h)**	**Replacement**
A6	0	0.017	0
A7	0.03	0	1
A8	0.07	0	0
A9	0	0.02	0
A10	0.017	0	0
A27	0	0.014	0
A32	0	0.034	0
A33 Inspection	0.05	0	0
Reuse	0	0	0
Scrap Part & Replace	0	0	1

Table A - 9 Activity costs for crankshaft remanufacture

Activity	Crankshaft		
	Labour (h)	**Machine (h)**	**Replacement**
A4	0.021	0	0
A6	0	0.017	0
A7	0.03	0	1
A8	0.07	0	0
A9	0	0.02	0
A10	0.017	0	0
A11	0.12	0	0
A14	0.2	0	0
A15	0	0.16	0
A21 Test	0.025	0	0
A22	0	0.15	0
A24	0	0.033	0
A27	0	0.017	0
A32	0	0.042	0
A33 Inspection	0.09	0	0
Reuse	0	0	0
Scrap Part & Replace	0	0	1

Table A - 10 Activity costs for flywheel remanufacture

Activity	Flywheel		
	Labour (h)	**Machine (h)**	**Replacement**
A4	0.017	0	0
A15	0	0.27	0
A24	0	0.026	0
A27	0	0.012	0
A32	0	0.036	0
A33 Inspection	0.05	0	0
Reuse	0	0	0
Scrap Part & Replace	0	0	1

Table A - 11 Activity costs for camshaft remanufacture

Activity	Camshaft		
	Labour (h)	**Machine (h)**	**Replacement**
A4	0.021	0	0
A11	0.12	0	0
A15	0	0.16	0
A21 Test	0	0.025	0
A22	0	0.15	0
A24	0	0.033	0
A27	0	0.017	0
A32	0	0.042	0
A33 Inspection	0.09	0	0
Reuse	0	0	0
Scrap Part & Replace	0	0	1

Table A - 12 Activity costs for turbo remanufacture

Activity	Turbo		
	Labour (h)	**Machine (h)**	**Replacement**
A1 Assembly	0.42	0	0
A2	0.03	0	0
A4	0.02	0	0
A12 Disassembly	0.008	0	0
A22	0	0.31	0
A32	0	0.04	0
A33 Inspection	0.05	0	0
Reuse	0	0	0
Scrap Part & Replace	0	0	1

A.2 Example B

Example B describes a cost estimation for the gearbox remanufacturer described within Case study 2. The example demonstrates the ability of the tool to cope with uncertain information. Here a simple product and process model are used, signifying estimation with little detailed information.

A.2.1 Product Model

The product model is described only at the top level with no sub components. The BoM structure is shown in Figure A - 13, whilst attribute information is described within Table A - 13. For gearboxes are listed representing the same gearbox but with different levels of information uncertainty.

Figure A - 13 BoM structure of the gearbox used in Example B

Table A - 13 Inforamtion requirements for gearbox product model, with four product examples showing varying amouts of uncertainity

	Manufacturer	**Power Rating (MW)**	**Condition**
Gearbox_A	Eickhoff	1.3	2
Gearbox_B	Eickhoff	1.3	*Unknown*
Gearbox_C	Eickhoff	*Unknown*	*Unknown*
Gearbox_D	*Unknown*	*Unknown*	*Unknown*

A.2.2 Process Model

The process model consists of a simple linear workflow consisting of three activities, shown in Figure A - 14. Each activity requires information to relate product attributes to historical costs. The weightings for each of these are listed within Table A - 14.

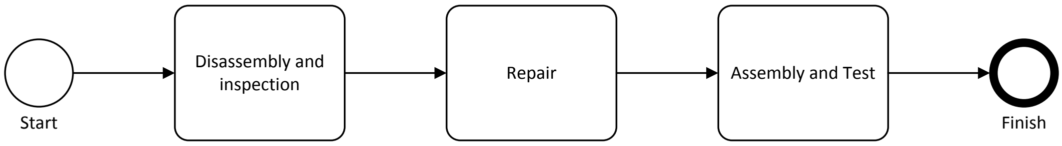


Figure A - 14 Simplified gearbox remanufacturing process

Table A - 14 Key attribute weighting values for each activity for use within Case Based Reasoning

	Match Type	**Disassembly and Inspection**	**Repair**	**Assembly and Test**
Manufacturer	Semantic	1	0.6	1
Power	Number	0.6	0.5	0.6
Condition	Number	0.1	1	0

A.2.3 Historical Job Information

Due to the short period of time this case study was operating, no data historical job records were collected to test the software tool. Instead the information displayed here has been generated, through intuitive parametric relationships for the purpose of testing the software tool. Product information is based upon data collected from case study.

Table A - 15 Historical job records with attribute values

	Manufacturer	Power (MW)	Condition
Gearbox_1	Eickhoff	1.0	4
Gearbox_2	Eickhoff	1.0	5
Gearbox_3	Eickhoff	1.5	1
Gearbox_4	ZF	1.5	1
Gearbox_5	Eickhoff	1.7	3
Gearbox_6	ZF	1.8	3
Gearbox_7	Bosch/Rexroth	1.8	4
Gearbox_8	Bosch/Rexroth	1.8	5
Gearbox_9	Eickhoff	2.0	3
Gearbox_10	ZF	2.0	3
Gearbox_11	Bosch/Rexroth	2.1	1
Gearbox_12	Eickhoff	2.1	1

Table A - 16 Historical job costs for each activity

	Disassembly and Inspection	Repair	Assembly and Test	Total
Gearbox_1	£9,605	£24,461	£11,721	£45,787
Gearbox_2	£10,478	£31,015	£12,321	£53,814
Gearbox_3	£12,375	£4,359	£13,397	£30,131
Gearbox_4	£15,582	£4,917	£14,786	£35,285
Gearbox_5	£15,582	£30,380	£15,510	£61,472
Gearbox_6	£18,344	£30,173	£18,967	£67,484
Gearbox_7	£19,444	£45,522	£21,095	£86,061
Gearbox_8	£17,772	£49,439	£18,316	£85,527
Gearbox_9	£17,698	£39,485	£19,828	£77,011
Gearbox_10	£19,868	£32,712	£25,645	£78,225
Gearbox_11	£19,444	£5,935	£24,508	£49,887
Gearbox_12	£16,865	£6,081	£20,858	£43,804

A.2.4 Results

Results of the cost estimation were calculated and shown below. Overall gearbox remanufacturing costs are highlighted within Table A - 17, whilst individual costs for each activity are shown in tables A -18 to A – 20.

Table A - 17 Cost and Risk results from Example B for the gearbox remanufacturing process

Number of iterations	10th Percentile (£)	Mean Cost (£)	90th Percentile (£)	Range (90th –10th) (£)
Gearbox_A	30355.1	50206.1	70335.7	39980.6
Gearbox_B	33903.6	55218.5	75822.0	41918.4
Gearbox_C	38820.5	58192.0	76433.9	37613.4
Gearbox_D	42053.9	62252.2	82597.1	40543.2

Table A - 18 Cost and Risk results from Example B for the disassembly and inspection activity

Number of iterations	10th Percentile (£)	Mean Cost (£)	90th Percentile (£)	Range (90^{th} –10^{th}) (£)
Gearbox_A	10648.2	14181.7	17892.9	7244.7
Gearbox_B	10265.6	13924.1	17437.4	7171.8
Gearbox_C	10455.0	15497.3	20044.5	9589.5
Gearbox_D	11742.1	16153.9	20292.3	8550.2

Table A - 19 Cost and Risk results from Example B for the repair activity

Number of iterations	10th Percentile (£)	Mean Cost (£)	90th Percentile (£)	Range (90^{th} –10^{th}) (£)
Gearbox_A	1091.0	20711.7	40178.9	39087.9
Gearbox_B	6682.9	25836.5	46189.4	39506.5
Gearbox_C	5993.9	24563.3	41278.1	35284.2
Gearbox_D	6580.9	27687.4	47950.2	41369.3

Table A - 20 Cost and Risk results from Example B for the assembly and test activity

Number of iterations	10th Percentile (£)	Mean Cost (£)	90th Percentile (£)	Range (90^{th} –10^{th}) (£)
Gearbox_A	11212.5	15312.7	19242.5	8030
Gearbox_B	10352.2	15457.9	19893.2	9541
Gearbox_C	12998.8	18131.4	24065.9	11067.1
Gearbox_D	13179.7	18410.9	24375.3	11195.6

A.3 Example C

Example C is based upon the same case study as Example B, however is shown in greater detail, highlighting the increased functionality of the cost estimation tool. Two product models are used to highlight how different product structures can be formed and used within the cost estimation tool. The process model is described along with historical job records and activity cost estimates.

A.3.1 Product Model 1

The first product model highlights a gearbox containing two planetary and one parallel transmission stage. The BoM structure is outlined within Figure A - 15, whilst attribute information is listed within tables A - 21 to A - 25.

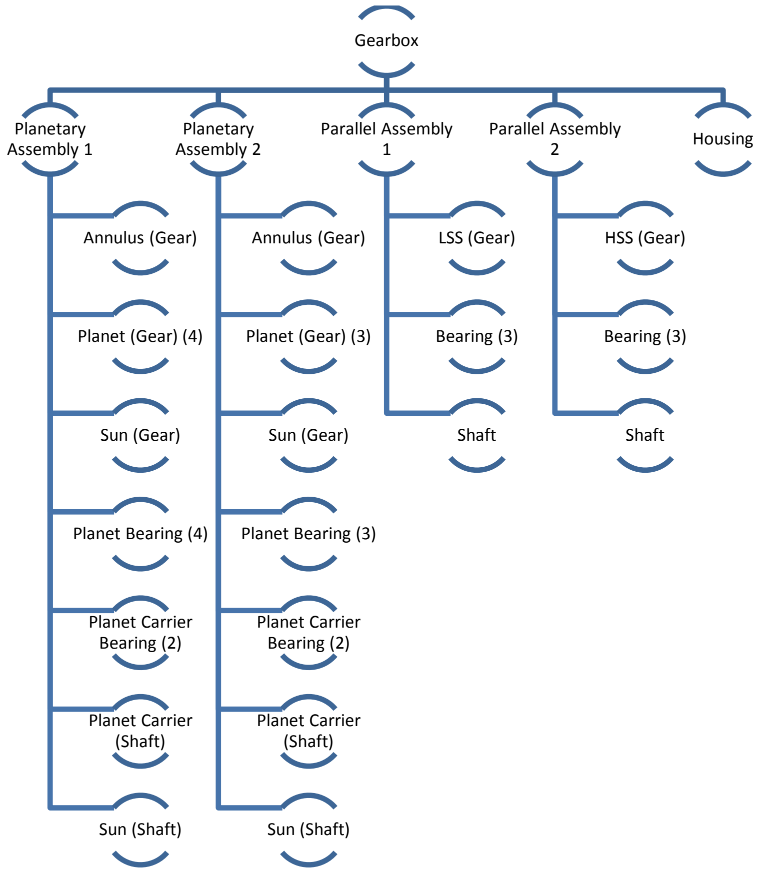


Figure A - 15 BoM and hierarchal structure of 2 stage planetary and 1 stage parallel, gearbox

	Manufacturer	**Power Rating (kW)**	**Condition**
Gearbox_A	Manufacturer_A	1900	3

Table A - 21 Transmission Assemblies for Gearbox 1

	Type	**Position**
Planetary_Assembly_1	Planetary	1
Planetary_Assembly_2	Planetary	2
Parallel_Assembly_1	Parallel	3
Parallel_Assembly_2	Parallel	4

Table A - 22 Gears for Gearbox 1

Parent Assembly	**Type**	**Diameter (mm)**	**Number of teeth**	**Condition (1-5)**
Planetary Assembly 1	Annulus	1860	*Unknown*	2
Planetary Assembly 1	Planet	500	*Unknown*	2
Planetary Assembly 1	Planet	500	*Unknown*	2
Planetary Assembly 1	Planet	500	*Unknown*	2
Planetary Assembly 1	Planet	500	*Unknown*	2
Planetary Assembly 1	Sun	95	*Unknown*	4
Planetary Assembly 2	Annulus	1500	*Unknown*	2
Planetary Assembly 2	Planet	400	*Unknown*	3
Planetary Assembly 2	Planet	400	*Unknown*	3
Planetary Assembly 2	Planet	400	*Unknown*	3
Planetary Assembly 2	Sun	75	*Unknown*	2
Parallel Assembly 1	Spur	110	*Unknown*	3
Parallel Assembly 2	Pinion	40	*Unknown*	3

Table A - 23 Bearings for Gearbox 1

Parent Assembly	**Manufacturer**	**Model**	**Rolling type**	**Inner Diameter (mm)**	**Condition (1-5)**
Planetary Assembly 1	Manufacturer_A	X5	Cylindrical Roller	500	4
Planetary Assembly 1	Manufacturer_A	X10	Cylindrical Roller	550	4
Planetary Assembly 1	Manufacturer_A	X2	Cylindrical Roller	340	4
Planetary Assembly 1	Manufacturer_A	X3	Cylindrical Roller	360	4
Planetary Assembly 1	Manufacturer_B	*Unknown*	*Unknown*	390	4
Planetary Assembly 1	Manufacturer_A	*Unknown*	*Unknown*	800	4
Planetary Assembly 2	*Unknown*	*Unknown*	*Unknown*	*Unknown*	2
Planetary Assembly 2	Manufacturer_B	*Unknown*	*Unknown*	440	1
Planetary Assembly 2	Manufacturer_C	*Unknown*	*Unknown*	750	2
Planetary Assembly 2	Manufacturer_C	*Unknown*	*Unknown*	*Unknown*	*Unknown*
Planetary Assembly 2	Manufacturer_A	*Unknown*	*Unknown*	*Unknown*	*Unknown*
Parallel Assembly 1	Manufacturer_D	*Unknown*	*Unknown*	*Unknown*	3
Parallel Assembly 1	*Unknown*	*Unknown*	*Unknown*	430	4
Parallel Assembly 1	*Unknown*	*Unknown*	*Unknown*	540	4
Parallel Assembly 2	*Unknown*	*Unknown*	*Unknown*	*Unknown*	4
Parallel Assembly 2	*Unknown*	*Unknown*	*Unknown*	600	4
Parallel Assembly 2	*Unknown*	*Unknown*	*Unknown*	600	4

Table A - 24 Shafts for Gearbox 1

Parent Assembly	**Position**	**Shaft Diameter**	**Length**
Planetary Assembly 1	Planet Carrier	*Unknown*	*Unknown*
Planetary Assembly 1	Sun	*Unknown*	*Unknown*
Planetary Assembly 2	Planet Carrier	*Unknown*	*Unknown*
Planetary Assembly 2	Sun	*Unknown*	*Unknown*
Parallel Assembly 1	Low Speed	*Unknown*	*Unknown*
Parallel Assembly 2	High Speed	*Unknown*	*Unknown*

Table A - 25 Housing for Gearbox 1

Manufacturer	**Width**	**Length**
Manufacturer_A	*Unknown*	*Unknown*

A.3.2 Product Model 2

The second product model highlights a gearbox containing one planetary and two parallel transmission stages. The BoM structure is outlined within Figure A - 15, whilst attribute information is listed within tables A – 26 to A - 31.

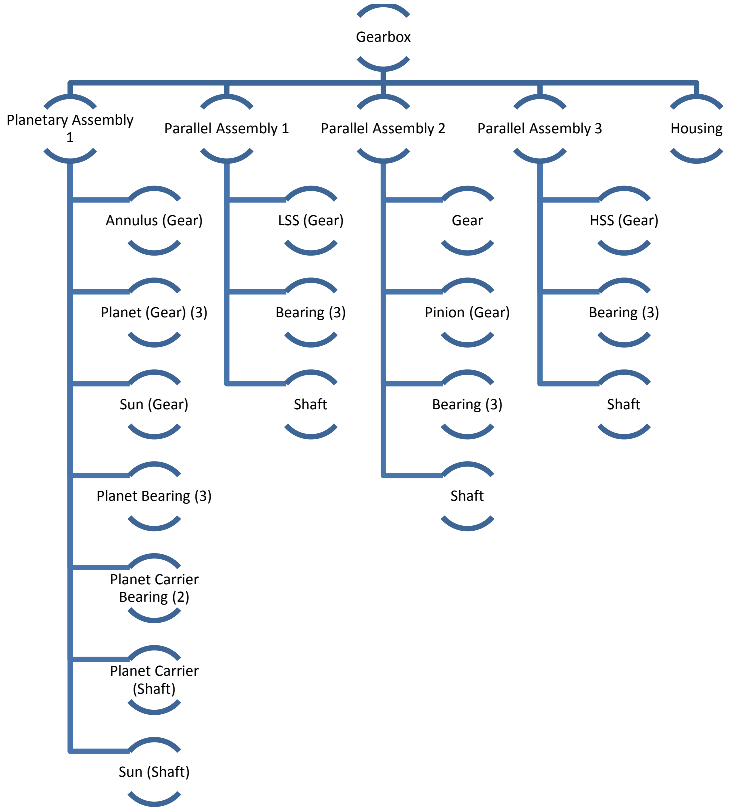


Figure A - 16 BoM and hierarchal structure of 1 stage planetary and 2 stage parallel

Table A - 26 Gearbox 2

	Manufacturer	**Power Rating (kW)**	**Condition**
Gearbox_A	Manufacturer_B	1200	3

Table A - 27 Transmission Assemblies for Gearbox 2

	Type	**Position**
Planetary Stage	Planetary	1
Parallel Stage	Parallel	2
Parallel Stage	Parallel	3
Parallel Stage	Parallel	4

Table A - 28 Gears for Gearbox 2

Parent Assembly	**Type**	**Diameter (mm)**	**Number of teeth**	**Condition (1-5)**
Planetary Assembly 1	Annulus	1860	*Unknown*	4
Planetary Assembly 1	Planet	500	*Unknown*	4
Planetary Assembly 1	Planet	500	*Unknown*	4
Planetary Assembly 1	Planet	500	*Unknown*	4

Planetary Assembly 1	Sun	95	*Unknown*	3
Parallel Assembly 1	Spur	*Unknown*	*Unknown*	1
Parallel Assembly 2	Pinion	*Unknown*	*Unknown*	2
Parallel Assembly 2	Spur	*Unknown*	*Unknown*	2
Parallel Assembly 3	Pinion	*Unknown*	*Unknown*	3

Table A - 29 Bearings for Gearbox 2

Parent Assembly	**Manufacturer**	**Model**	**Rolling type**	**Inner Diameter (mm)**	**Condition (1-5)**
Planetary Assembly 1	Manufacturer_A	X5	Cylindrical Roller	500	2
Planetary Assembly 1	Manufacturer_A	X10	Cylindrical Roller	550	3
Planetary Assembly 1	Manufacturer_A	X2	Cylindrical Roller	340	3
Planetary Assembly 1	Manufacturer_B	*Unknown*	*Unknown*	390	3
Planetary Assembly 1	Manufacturer_A	*Unknown*	*Unknown*	800	3
Parallel Assembly 1	Manufacturer_D	*Unknown*	*Unknown*	*Unknown*	3
Parallel Assembly 1	*Unknown*	*Unknown*	*Unknown*	430	3
Parallel Assembly 1	*Unknown*	*Unknown*	*Unknown*	540	2
Parallel Assembly 2	*Unknown*	*Unknown*	*Unknown*	*Unknown*	4
Parallel Assembly 2	*Unknown*	*Unknown*	*Unknown*	600	3
Parallel Assembly 2	*Unknown*	*Unknown*	*Unknown*	600	3
Parallel Assembly 3	*Unknown*	*Unknown*	*Unknown*	*Unknown*	3
Parallel Assembly 3	*Unknown*	*Unknown*	*Unknown*	*Unknown*	3
Parallel Assembly 3	*Unknown*	*Unknown*	*Unknown*	*Unknown*	3

Table A - 30 Shafts for Gearbox 2

	Position	**Shaft Diameter**	**Length**
Planetary Assembly 1	Planet Carrier	*Unknown*	*Unknown*
Planetary Assembly 1	Sun	*Unknown*	*Unknown*
Parallel Assembly 1	Low Speed	*Unknown*	*Unknown*
Parallel Assembly 2	Intermediate	*Unknown*	*Unknown*
Parallel Assembly 3	High Speed	*Unknown*	*Unknown*

Table A - 31 Housing for Gearbox 2

Manufacturer	**Width**	**Length**
Manufacturer_B	*Unknown*	*Unknown*

A.3.3 Process Model

The process model is outlined through five process workflows comprising of a top level workflow and four sub processes, shown in figures A -17 to A -21. The activities outlined within these workflows are described within Table A - 32, whist exclusive gateway information is shown in Table A - 33. The same process model is used for both of the product models.

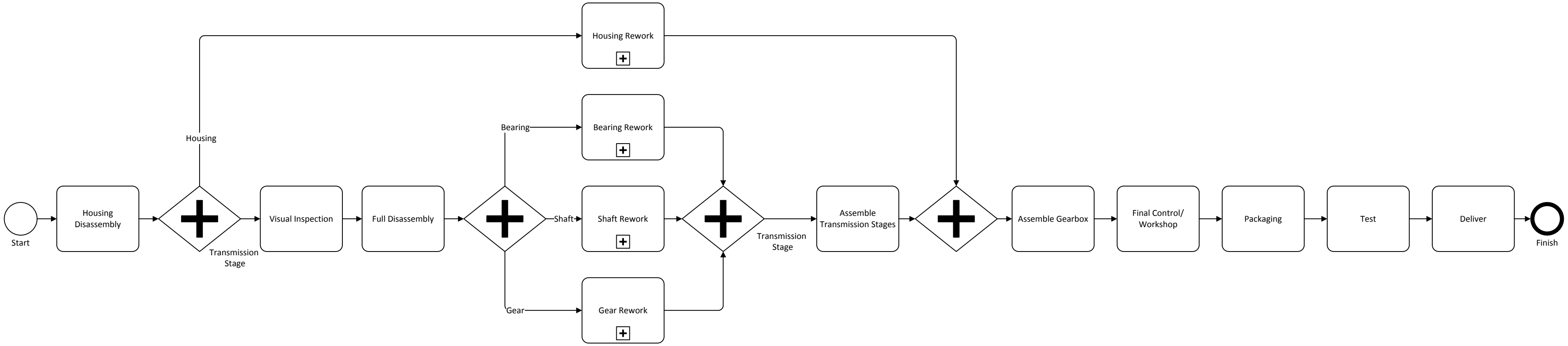


Figure A - 17 Top Level Gearbox remanufacturing process

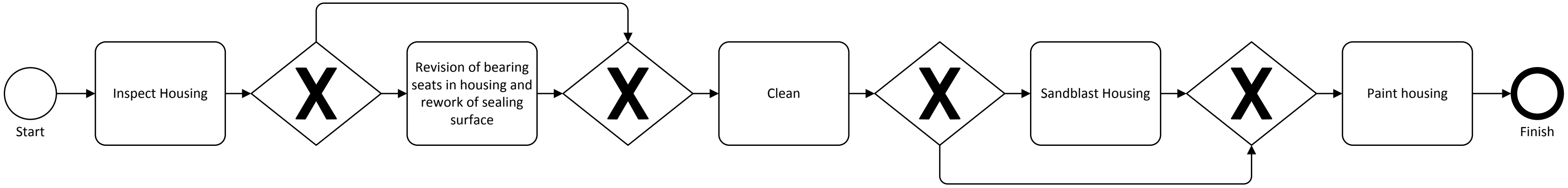


Figure A - 18 Housing Rework Sub process

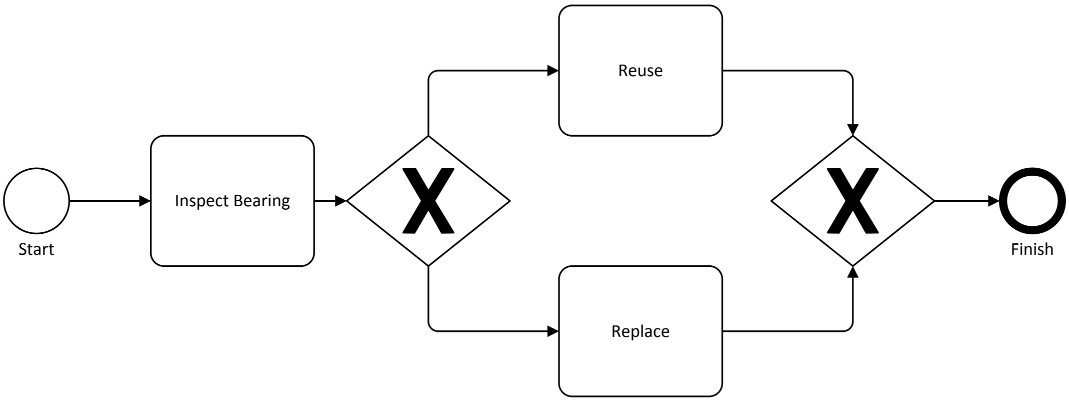


Figure A - 19 Bearing Rework

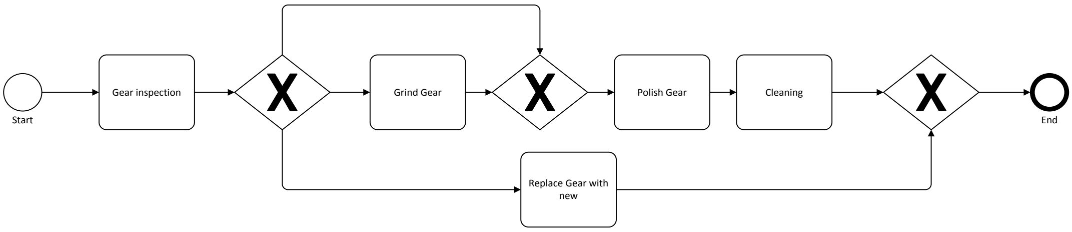


Figure A - 20 Gear Rework

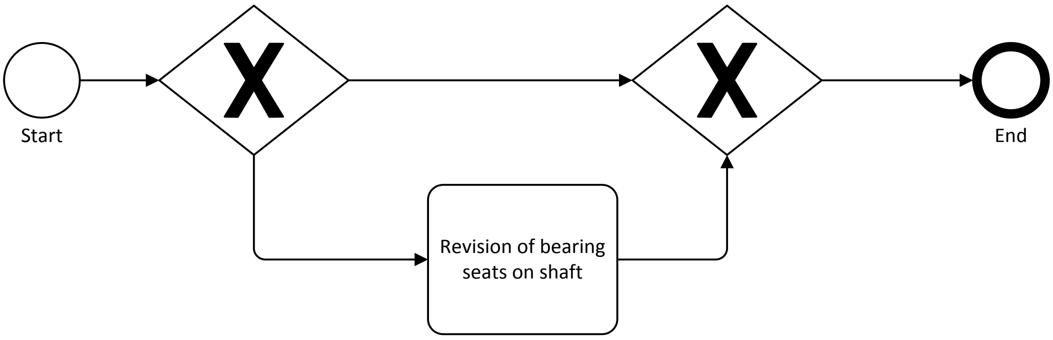


Figure A - 21 Shaft Rework

Table A - 32 Activity Details

Activity ID	Activity Name	Description	Component/s Input	Component/s Outputs	CBR Key Attributes
A1	Housing Disassembly & visual inspection	Removal of upper housing components from gearbox to allow visual inspection.	Gearbox	Housing, Transmission stages	Manufacturer,
A2	Full Disassembly	Removal of transmission stages from remaining housing and disassemble of each transmission into individual components.	Transmission stages	Bearings, Shafts, Gears	Transmission type, Manufacturer,
A3	Transmission Assembly	Assembly of transmission stages from bearings, shafts and gears.	Bearings, Shafts, Gears	Transmission stages	Transmission type, Manufacturer,
A4	Assemble Gearbox	Assembly of gearbox from transmission stages	Gearbox	Gearbox	Manufacturer
A5	Final Control/ Workshop	Assembly of lubrication system and sensors	Gearbox	Gearbox	Manufacturer, Power
A6	Packaging	Package gearbox to be sent to the testing facility	Gearbox	Gearbox	Manufacturer, Power
A7	Testing	Testing of gearbox	Gearbox	Gearbox	Power
A8	Inspect Bearing	Identify the type of bearing for replacement	Bearing	Bearing	Inner Diameter, Rolling type, Model
A9	Reuse Bearing	Directly reuse the bearing	Bearing	Bearing	N/A
A10	Replace Bearing	Replace bearing from an external manufacturer	Bearing	Bearing	Inner Diameter, Rolling type, Manufacturer, Model
A11	Gear Inspection	Inspection of a gear to determine appropriate correction method	Gear	Gear	Diameter, Number of teeth, Gear Type
A12	Gear Grind	Grind the gear to remove abrasions	Gear	Gear	Diameter, Number of teeth, Gear Type
A13	Polish Gear	Polish gear to desired level	Gear	Gear	Diameter, Number of teeth, Gear Type
A14	Clean Gear	Clean gear to remove remaining debris	Gear	Gear	Diameter, Number of teeth, Gear Type
A15	Replace Gear with new	Replace the existing gear with a newly manufactured one	Gear	Gear	Diameter, Number of teeth, Gear Type
A16	Revision of bearing seats on shaft	Adjust bearing seats on the shaft to meet the desired tolerance	Shaft	Shaft	Shaft Diameter
A17	Inspect Housing	Inspect housing to determine required work	Housing	Housing	Manufacturer,
A18	Clean Housing	Clean the housing of oil and debris	Housing	Housing	Manufacturer, Length, Width
A19	Revision of	Adjust bearing seats in	Housing	Housing	Manufacturer,

	bearing seats in housing and rework of sealing surface	the housing to meet the desired tolerance			Length, Width
A20	Sandblast Housing	Sandblasting of the housing to smooth surface and remove paint.	Housing	Housing	Manufacturer, Length, Width
A21	Paint Housing	Paint housing	Housing	Housing	Manufacturer, Length, Width

A.3.4 Gateway Membership Functions

The information used to describe the exclusive gateways are detailed within this section. Each exclusive gateway is described within Table A - 33, with the fuzzy membership functions shown within Figures A – 22 to A - 23.

Table A - 33 Gateway Details

Gateway ID	Sub process	Description	Decision Attribute	Membership Functions
Housing Seat Revision?	Housing	An assessment to determine whether bearing seat revision is required	N/A	Figure A - 22
Housing Sandblasting?	Housing	Determines whether sandblasting is required	N/A	Figure A - 23
Bearing sourcing location	Bearing	Determines where the bearing replacements are sourced	Inner Diameter	Figure A - 24
Gear Rework	Gear	Determines the rework process for each gear	Gear Condition	Figure A - 25
Shaft Rework	Shaft	Determines the rework process for each shaft	N/A	Figure A - 26

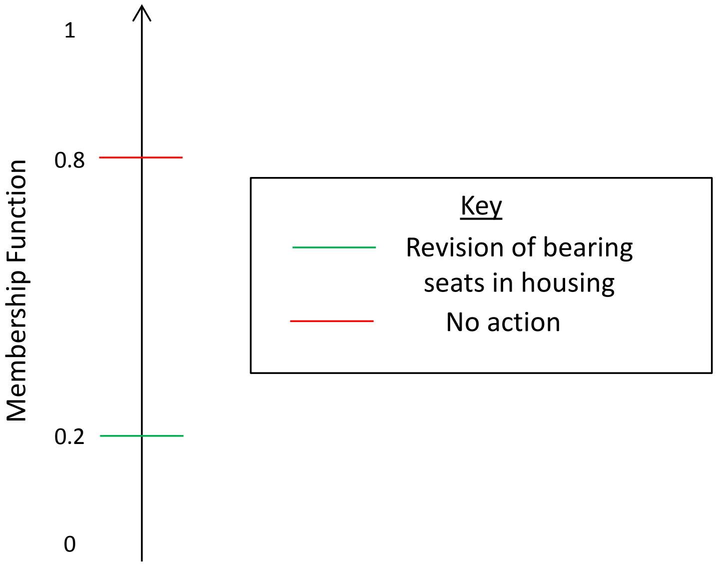


Figure A - 22 Membership function for the housing seat revision gateway

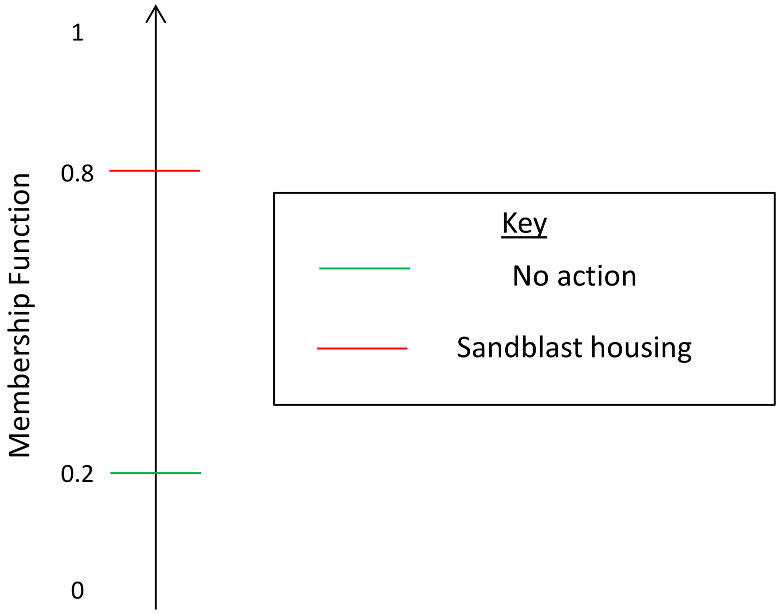


Figure A - 23 Membership function for housing sandblasting gateway

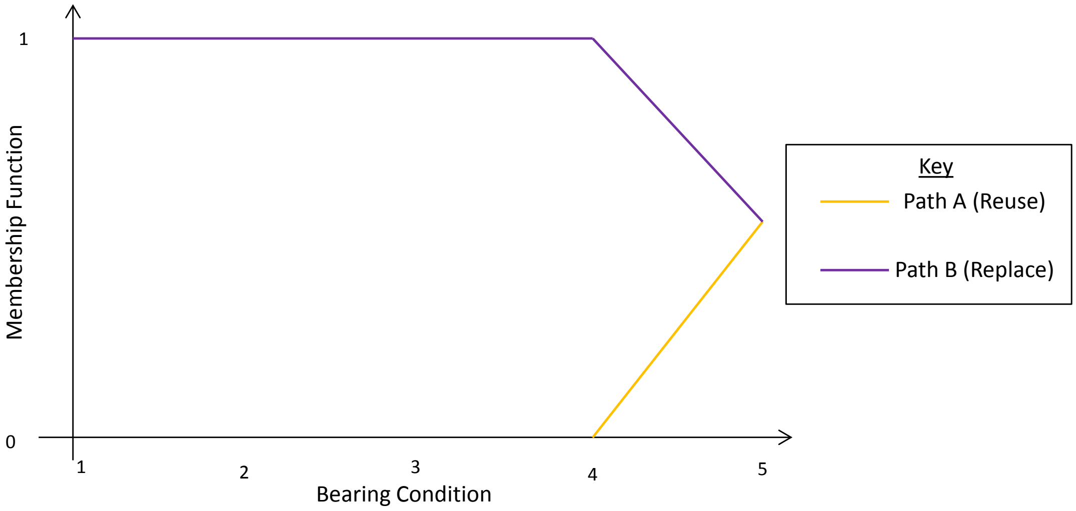


Figure A - 24 Membership function for the bearing sourcing location gateway

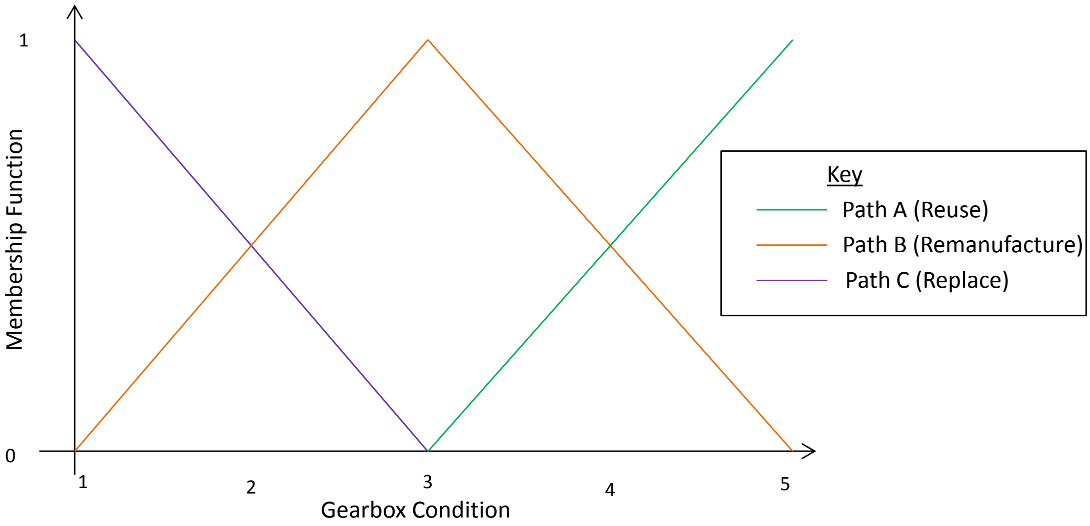


Figure A - 25 Membership function for the gear rework gateway

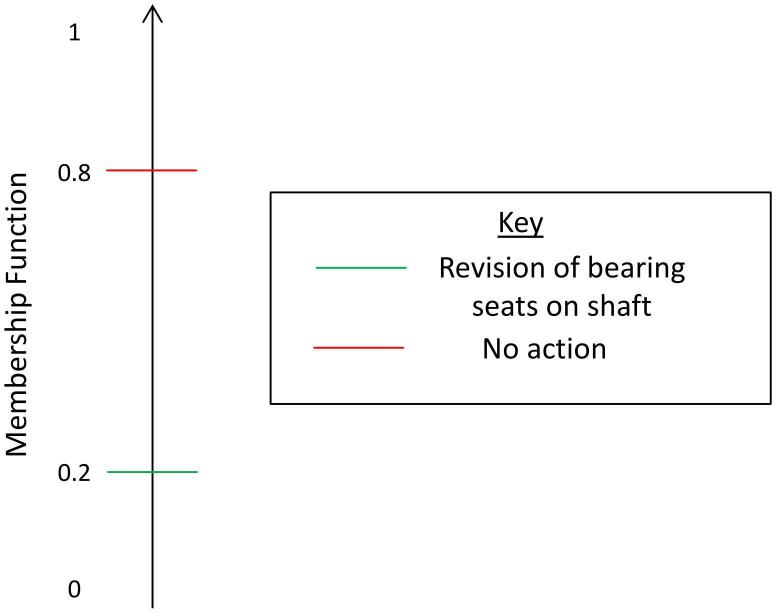


Figure A - 26 Membership function for the revision of bearing seats on shaft decision gateway

A.3.5 Historical Job Records

Historical job records are shown within this section. Information has been generated to represent past remanufacturing cases and are recorded at a component level. Twelve historical cases have been created for each component type, with attribute information stored in tables A - 34 to A - 38 and cost information recorded in tables A – 39 to A – 43.

Table A - 34 Historical job gearbox records

	Manufacturer	Power (MW)	Number of Planetary Stages	Number of Spur Stages	Condition
Gearbox_1	Eickhoff	1.0	1	2	4
Gearbox_2	Eickhoff	1.0	1	2	5
Gearbox_3	Eickhoff	1.5	1	2	1
Gearbox_4	ZF	1.5	1	2	1
Gearbox_5	Eickhoff	1.7	1	2	3
Gearbox_6	ZF	1.8	2	1	3
Gearbox_7	Bosch/Rexroth	1.8	1	2	4
Gearbox_8	Bosch/Rexroth	1.8	2	1	5
Gearbox_9	Eickhoff	2.0	2	1	3
Gearbox_10	ZF	2.0	2	1	3
Gearbox_11	Bosch/Rexroth	2.1	2	1	1
Gearbox_12	Eickhoff	2.1	2	1	1

Table A - 35 Historical job housing records

	Manufacturer	Length (m)	Width (m)
Housing_1	Eickhoff	2.7	2.5
Housing_2	Eickhoff	2.7	2.5
Housing_3	Eickhoff	3	2.8
Housing_4	ZF	3	2.8
Housing_5	Eickhoff	3.2	2.9
Housing_6	ZF	3.2	2
Housing_7	Bosch/Rexroth	3.3	3
Housing_8	Bosch/Rexroth	3.3	2.1
Housing_9	Eickhoff	3.4	2.1
Housing_10	ZF	3.4	2.2
Housing_11	Bosch/Rexroth	3.5	2.2
Housing_12	Eickhoff	3.5	2.2

Table A - 36 Historical job gear records

	Gear Type	Diameter (mm)	Number of teeth	Condition
Gear_1	Annulus	1850	232	3
Gear_2	Sun	530	67	4
Gear_3	Planet	350	44	3
Gear_4	Planet	300	38	2
Gear_5	Planet	320	40	3
Gear_6	Spur	1080	136	1
Gear_7	Spur	340	43	3
Gear_8	Spur	700	88	2
Gear_9	Annulus	2000	251	4
Gear_10	Sun	500	63	5
Gear_11	Planet	400	50	2
Gear_12	Planet	370	46	3

Table A - 37 Historical job bearing records

Case ID	Manufacturer	Model	Rolling type	Inner Diameter (mm)
Bearing_1	Manufacturer_A	X4	Cylindrical Roller	420
Bearing_2	Manufacturer_A	X3	Cylindrical Roller	360
Bearing_3	Manufacturer_A	X8	Cylindrical Roller	500
Bearing_4	Manufacturer_B	W2	Cylindrical Roller	450
Bearing_5	Manufacturer_D	Z3	Ball Bearing	525
Bearing_6	Manufacturer_D	Z7	Cylindrical Roller	600
Bearing_7	Manufacturer_B	W1	Cylindrical Roller	350
Bearing_8	Manufacturer_B	W1	Cylindrical Roller	350
Bearing_9	Manufacturer_C	Y2	Cylindrical Roller	425
Bearing_10	Manufacturer_C	Y17	Ball Bearing	380
Bearing_11	Manufacturer_A	X11	Cylindrical Roller	785
Bearing_12	Manufacturer_D	Z4	Cylindrical Roller	900

Table A - 38 Historical job shaft records

	Position	Shaft Diameter	Length
Shaft_1	Planet Carrier	221	0.8
Shaft_2	Planet Carrier	227	1.2
Shaft_3	High Speed	206	1.5
Shaft_4	High Speed	215	1.4
Shaft_5	Intermediate	235	1
Shaft_6	Low Speed	204	0.7
Shaft_7	Low Speed	229	0.8
Shaft_8	Low Speed	239	0.9
Shaft_9	Sun Shaft	211	0.8
Shaft_10	Sun Shaft	212	0.7
Shaft_11	Sun Shaft	208	0.6
Shaft_12	Planet Carrier	239	1

Table A - 39 Bearing level activity costs

	Inspect Bearing (£)	Reuse Bearing (£)	Replace Bearing (£)
Bearing_1	30	0	501
Bearing_2	30	0	519
Bearing_3	30	0	545
Bearing_4	30	0	1111
Bearing_5	30	0	1637
Bearing_6	30	0	2815
Bearing_7	30	0	1365
Bearing_8	30	0	1365
Bearing_9	30	0	1428
Bearing_10	30	0	1316
Bearing_11	30	0	1054
Bearing_12	30	0	3992

Table A - 40 Gearbox level activity costs

	Housing Disassembly & visual inspection (£)	Full Disassembly (£)	Transmission Assembly (£)	Assemble Gearbox (£)	Final Control/ Workshop (£)	Packaging (£)	Testing (£)
Gearbox_1	943	8681	3586	2229	457	300	2000
Gearbox_2	918	8586	3734	2177	458	300	2000
Gearbox_3	927	8264	3537	2262	436	300	2000
Gearbox_4	954	9110	3562	2561	521	300	2000
Gearbox_5	990	8923	3530	2280	456	300	2000
Gearbox_6	1055	10025	4955	4062	832	300	2000
Gearbox_7	918	10712	3628	2727	550	300	2000
Gearbox_8	1094	11761	4664	4355	843	300	2000
Gearbox_9	1102	9046	4726	3461	690	300	2000
Gearbox_10	1085	10035	4792	4151	807	300	2000
Gearbox_11	1001	11023	4677	4196	869	300	2000
Gearbox_12	1037	9185	4776	3575	752	300	2000

Table A - 41 Housing level activity costs

	Inspect Housing (£)	Clean Housing (£)	Revision of bearing seats in housing and rework of sealing surface (£)	Sandblast Housing (£)	Paint Housing (£)
Housing_1	500	337.5	1696	200	405
Housing_2	500	337.5	1686	200	405
Housing_3	500	420	2184	200	504
Housing_4	500	420	2125	200	504
Housing_5	500	464	2340	200	556.8
Housing_6	500	320	1572	200	384
Housing_7	500	495	2410	200	594
Housing_8	500	346.5	1790	200	415.8
Housing_9	500	357	1763	200	428.4
Housing_10	500	374	1836	200	448.8
Housing_11	500	385	1840	200	462
Housing_12	500	385	1931	200	462

Table A - 42 Shaft level activity costs

	Revision of bearing seats on shaft (£)	No Action required (£)
Shaft_1	525	0
Shaft_2	523	0
Shaft_3	522	0
Shaft_4	486	0
Shaft_5	504	0
Shaft_6	517	0
Shaft_7	484	0
Shaft_8	519	0
Shaft_9	500	0
Shaft_10	501	0
Shaft_11	496	0
Shaft_12	475	0

Table A - 43 Gear level activity costs

	Gear Inspection (£)	Gear Grind (£)	Polish Gear (£)	Clean Gear (£)	Replace Gear with new (£)
Gear_1	463	*N/A*	940	573	*N/A*
Gear_2	133	*N/A*	268	156	*N/A*
Gear_3	88	*N/A*	175	103	*N/A*
Gear_4	75	233	150	86	*N/A*
Gear_5	80	*N/A*	160	97	*N/A*
Gear_6	270	*N/A*	*N/A*	*N/A*	4886
Gear_7	85	*N/A*	172	99	*N/A*
Gear_8	175	538	359	210	*N/A*
Gear_9	500	*N/A*	985	616	*N/A*
Gear_10	125	*N/A*	251	150	*N/A*
Gear_11	100	335	197	122	*N/A*
Gear_12	93	*N/A*	183	111	*N/A*

A.3.6 Activity Cost Estimates

The final costs information required are those of the activity estimates. For this example, the bearing costs for certain models are known, and are shown within Table A - 44.

Table A - 44 Bearing replacement cost estimates

ID	Manufacturer	Model	Bearing Replacement (£)
1	Manufacturer_A	X1	400
2	Manufacturer_A	X2	432
3	Manufacturer_A	X3	519
4	Manufacturer_A	X4	501
5	Manufacturer_A	X5	650

Appendix B Publications

Adapting the 'Iron Triangle' to Develop a Framework for Reverse Manufacturing Decision Support Tools

P. A. Goodall, E. L. Rosamond, L. M. Justham, J. A. Harding

Abstract - Interest from industry in reverse manufacturing is increasing due to market drivers such as higher costs for resources and increasing government legislation aimed at reducing waste. In order for companies to take advantage of this business opportunity, awareness and understanding of the role of uncertainty within reverse manufacturing and its influence on performance parameters of cost, time and quality must be acknowledged. Although decision support tools exist in literature, they currently lack a holistic approach in modelling the interrelated effects of performance parameters and uncertainty within the business. The purpose of this paper therefore is to propose a framework in which future decision tools can be created for reverse manufacturing. The effects of this framework are then demonstrated with current business scenarios, using reverse manufacturing case study examples.

Proceedings of the 19th ISPE International Conference on Concurrent Engineering, Concurrent Engineering Approaches for Sustainable Product Development in a Multi-Disciplinary Environment 2013, pp 475-484

A review of the state of the art in tools and techniques used to evaluate remanufacturing feasibility

Paul Goodall, Emma Rosamond, Jenifer Harding

Abstract - Remanufacturing often seems a sensible approach for companies looking to adopt sustainable business plans to achieve long term success. However, remanufacturing must not be treated as a panacea for achieving a sustainable business, as issues such as market demand, product design, end of life condition and information uncertainty can affect the success of a remanufacturing endeavour. Businesses therefore need to carefully assess the feasibility of adopting remanufacturing before committing to a particular activity or strategy. To aid this decision process, a number of tools and techniques have been published by academics. However, there is currently not a formal review and comparison of these tools and how they relate to the decision process.

The main research objective of this study has therefore been to identify tools and methods which have been developed within academia to support the decision process of assessing and evaluating the viability of conducting remanufacturing, and evaluate how they have met the requirements of the decision stage. This has been achieved by conducting a content analysis. Three bibliographic databases were searched (Compendex, Web of Science and Scopus) using a structured keyword search to identify relevant literature. The identified tools were then split into 6 categories based upon the specific decision stages and applications, then evaluated against a set of key criteria which are, the decision factors (economic, environmental, social) and the inclusion of uncertainty. The key finding of this study has been that although decision factors are generally well covered, operational tools and the use of uncertainty are often neglected.

Journal of Cleaner Production, Volume 81, 15 October 2014, Pages 1–15